Conceptual Design of the LBNF Target Station, Decay Pipe and Absorber

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Outline

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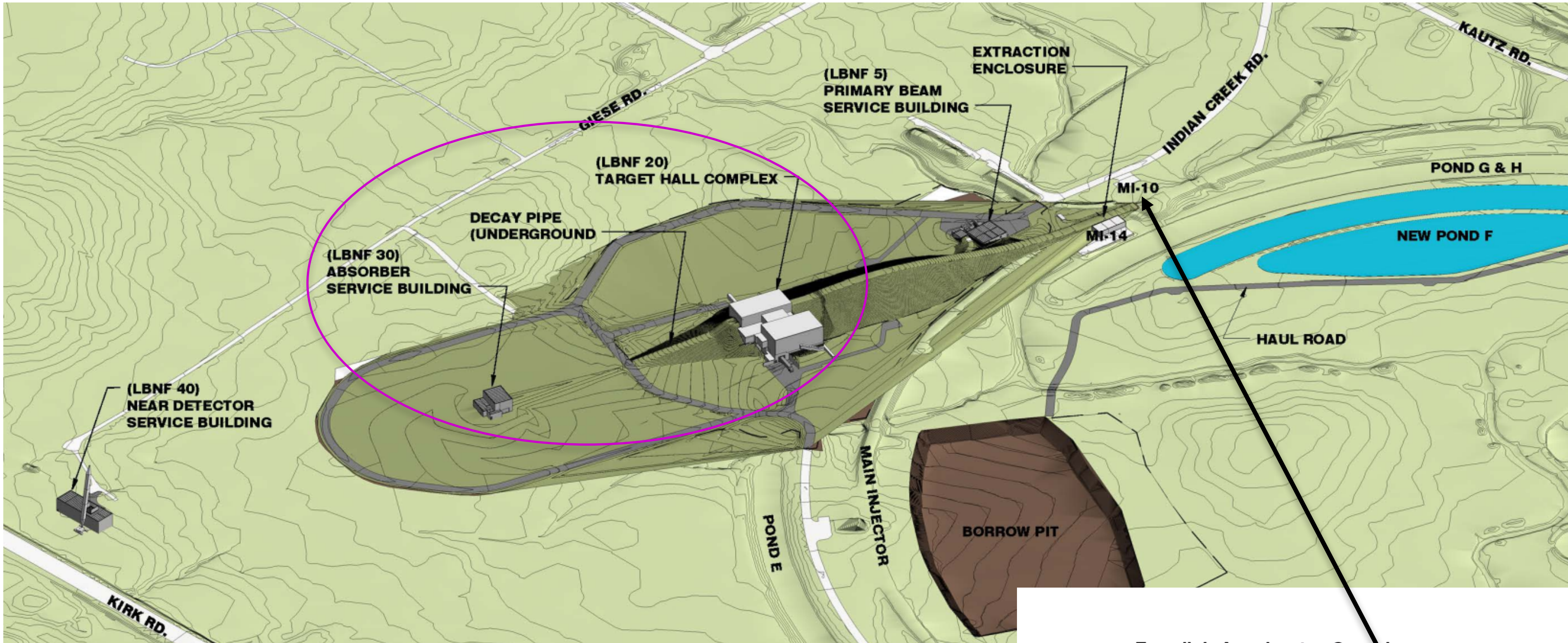
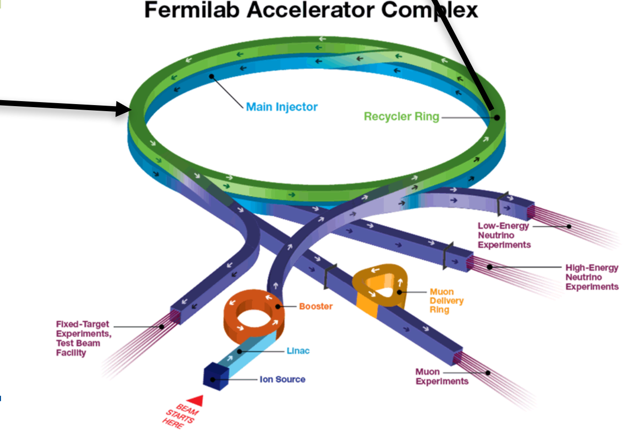
  - Requirements & Assumptions
  - Energy Deposition in the Neutrino Beam Components
- Target Station Conceptual Design
  - Target Complex (Civil infrastructure)
  - Target Shield Pile
- Decay Pipe Conceptual Design
  - Decay Pipe Structure & Cooling
  - Beam Windows
- Absorber Conceptual Design
- Summary & Conclusion

Long-Baseline Neutrino Facility at Fermilab

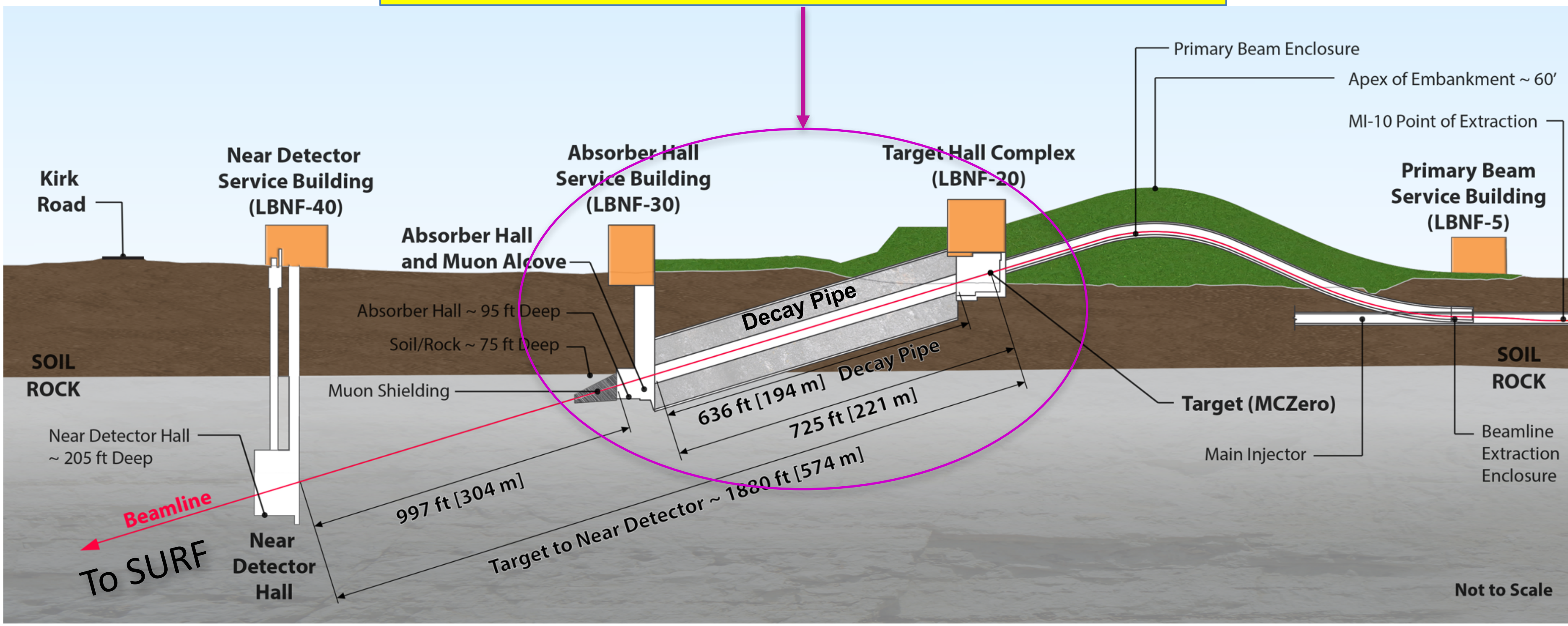




Long-Baseline Neutrino Facility at Fermilab

Beam Extraction at Main Injector MI-10

LBNF Neutrino Beamline
Target Station, Decay Pipe, and Absorber



Tunneled excavation

Constructed in Open Cut

Facility designed for 1.2 MW initial operation [PIP-II], upgradeable to 2.4 MW [PIP-III]

Neutrino Beam Facility – Requirements and Assumptions

- All systems designed for 1.2 MW initial proton beam power and facility is upgradeable to 2.4 MW proton beam power.
- All systems that are prone to failure, such as water-cooled systems, are designed to be repairable and/or replaceable.
- Stringent limits placed on radiological protection of environment, members of public and workers. Entire facility encapsulated in water-proof barrier.
- Facility is assumed to be able to operate for a 30 year span. Design life of Target & Absorber Hall Complexes and of Decay Pipe is 50 years; design life of water barrier system around them is 80 years.
- Uptime (including the accelerator complex): aiming for at least 55%
- 6-cell storage morgue with sufficient space for 2yrs of 1.2 MW running, Fermilab to provide additional storage for radioactive components.
- Actively implementing lessons learned from NuMI/MINOS/NOvA and other Facilities.

Systems being designed for 2.4 MW

- Following systems are designed for 2.4 MW since upgrading later would be prohibitively expensive and inconsistent with ALARA principles:
  - Size of enclosures (target chase, target hall, decay pipe, absorber hall)
  - Radiological shielding of enclosures (except for the target hall roof, which can be easily upgraded for 2.4 MW when needed)
  - Water cooled target chase cooling panels
  - Decay pipe and its cooling and the decay pipe downstream window
  - Beam Absorber
  - Remote handling equipment
  - Radioactive water system piping
  - Horn support structures designed to last for the facility lifetime.

Energy Deposition in the Neutrino Beam Components @ 2.4 MW

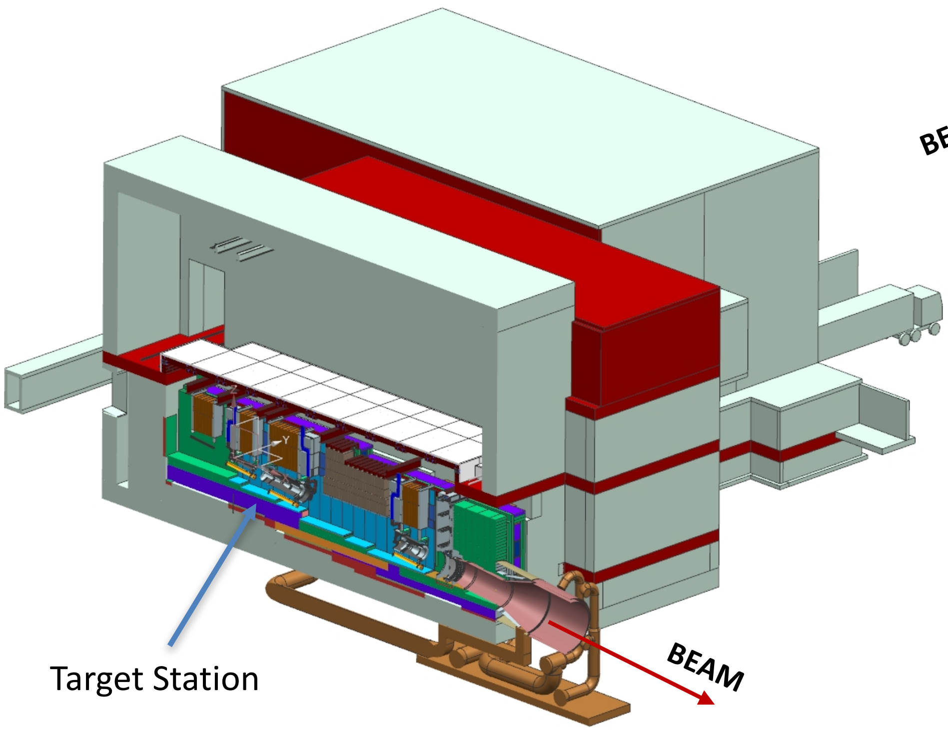
All results are for 120 GeV @ 2.4 MW	Power Dissipation (kW) Reference Design	Optimized Design	Ratio OPT/REF
Target Station	**952**	**1238**	**1.30**
Target/Horns	***154***	***194***	***1.26***
Target	30	56	1.90
Horns	124	138	1.11
Steel Shield Pile Assembly	***770***	***1004***	***1.30***
Chase Cooling Panels (including the bottom 4 inch of T-blocks)	462	594	1.28
Bulk steel shielding blocks/elements	308	410	1.33
Concrete Blocks (Bath Tub)	***0.201***	***0.132***	***0.66***
Miscellaneous	***28***	***40***	***1.43***
Decay Pipe & DS Window	**452**	**542**	**1.20**
Double-walled steel decay pipe	***291***	***350***	***1.20***
Concrete shielding	***158***	***189***	***1.20***
Downstream SS window	***0.08***	***0.06***	***0.75***
Downstream steel frame	***2.70***	***2.80***	***1.04***
Hadron Absorber	**786**	**400**	**0.51**
Neutrino Power	**66**	**69**	**1.05**
Miscellaneous	**144**	**151**	**1.05**
2.4-MW LBNF EDEP (kW) Total	**2400**	**2400**	

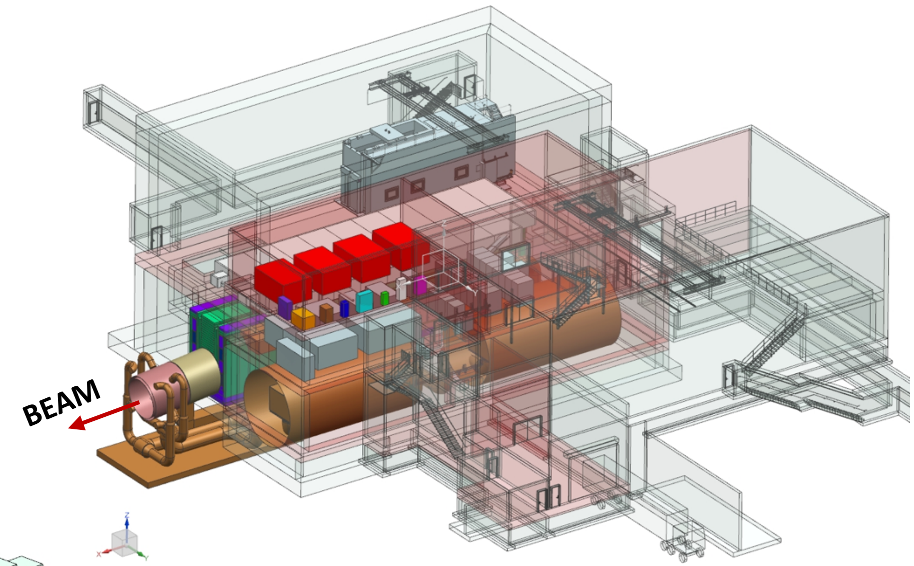
Table shows the results for both Reference & Optimized Designs.

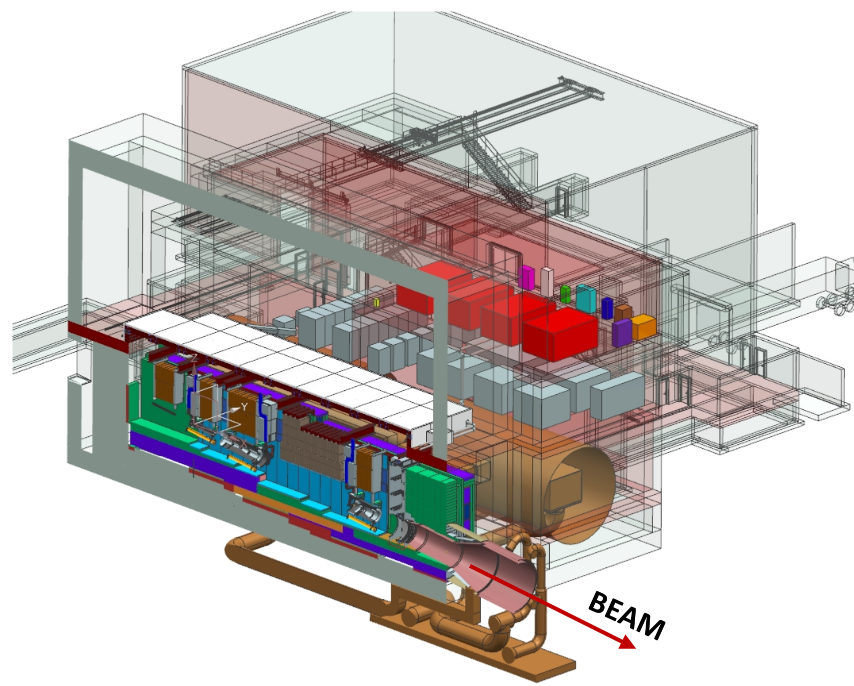
Component thermal and stress analysis results are presented for the worst case.

Target Station Design
(*Conceptual*)

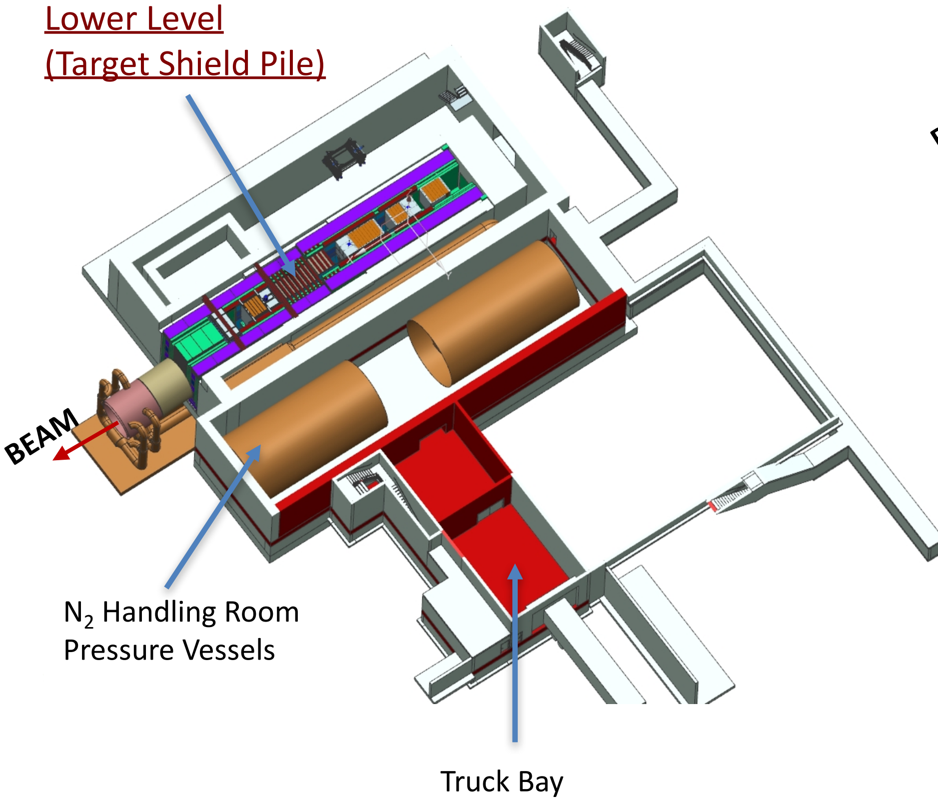
LBNF Target Complex

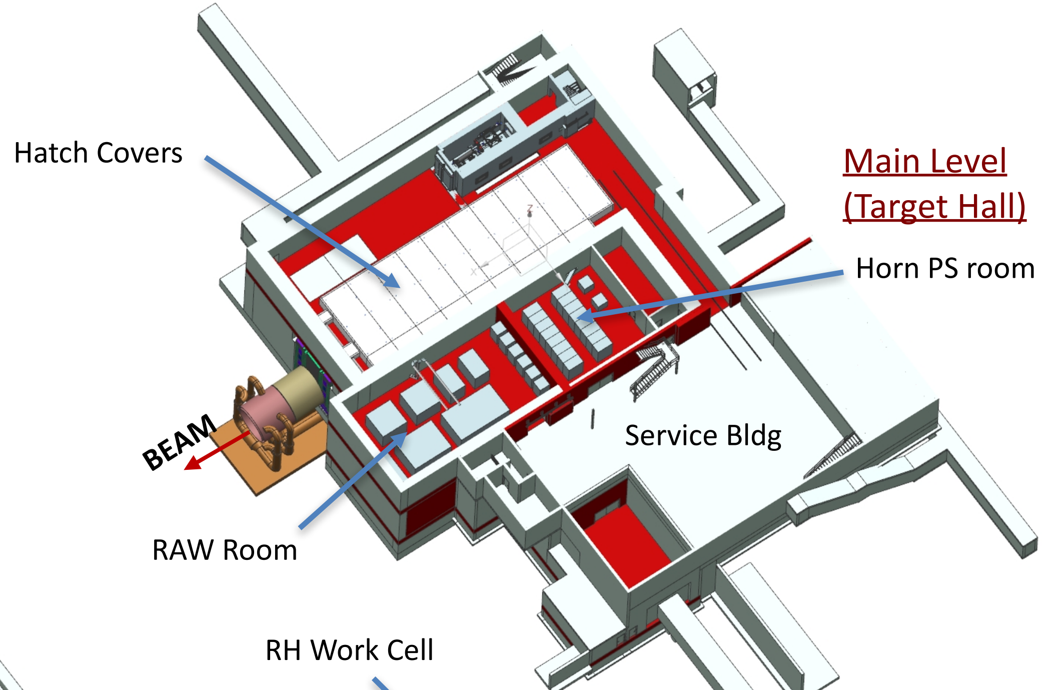


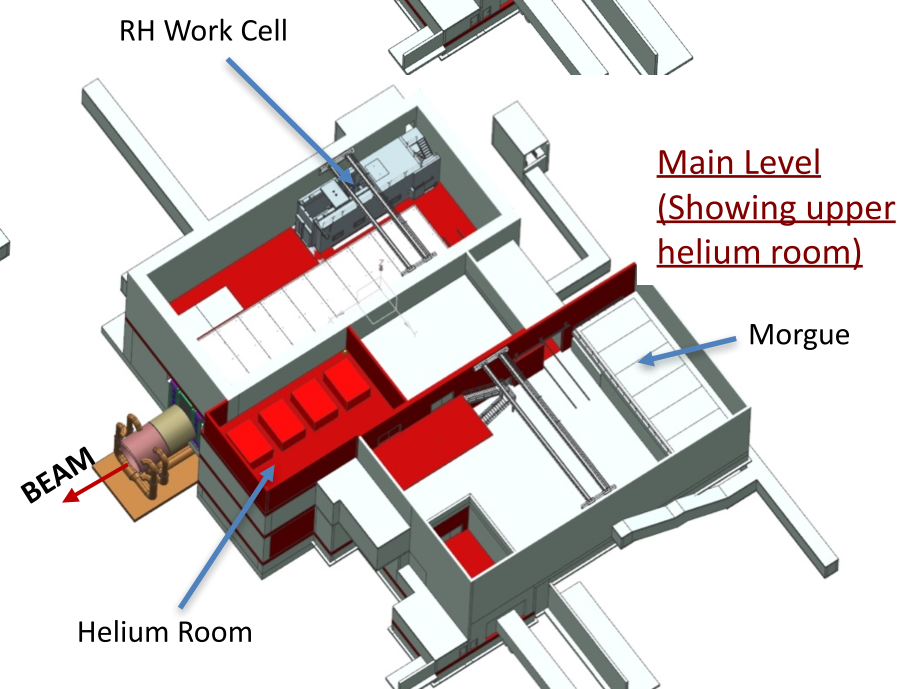




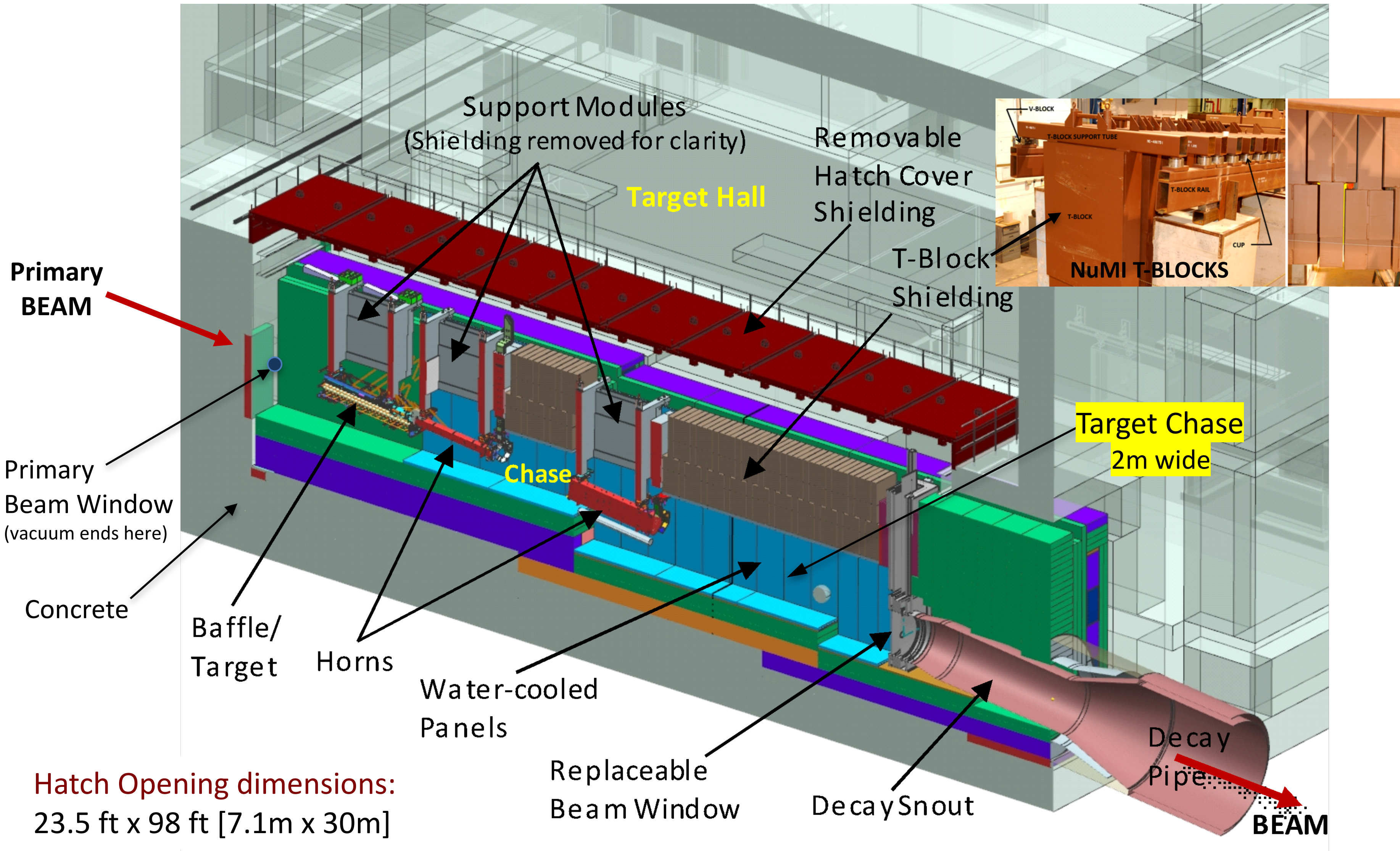
LBNF Target Complex Plan View







LBNF Target Shield Pile (Reference 2-horn Design)



Hatch Opening dimensions:
23.5 ft x 98 ft [7.1m x 30m]

Target Station Overview

- Target Shield Pile is designed for 2.4 MW beam power – once activated by beam, the shielding cannot be easily modified or upgraded later.
- Based on proven NuMI design – top loading of components with all feedthroughs from the side through a shield wall (called the "battlement").
- Special support modules place and align components inside the target chase. Modules rest on carriage beams that are supported on the outer concrete walls for thermal (alignment) stability. Steel "T-blocks" fill the top of the target chase.
- Recent decision to change to inert gas (N_2) as the gas medium:
  - Air-release studies for the longer and wider target chase showed that air in the target chase is no longer viable taking into account existing regulations and assumptions plus the safety factors we want and need to maintain (driven mainly by exceedance of ^{41}Ar releases). Inert gas in target chase also mitigates any corrosion issues.
- Target Shield Pile is both water cooled using special cooling panels placed inside the chase, and forced gas cooled (similar to NuMI).
- Small, controlled leaks are part of the tritium mitigation strategy.

Target Station – Target Shield Pile Design

Bulk steel shielding: 10,000 tons (9.1M Kg)

From Fermilab stockpile:

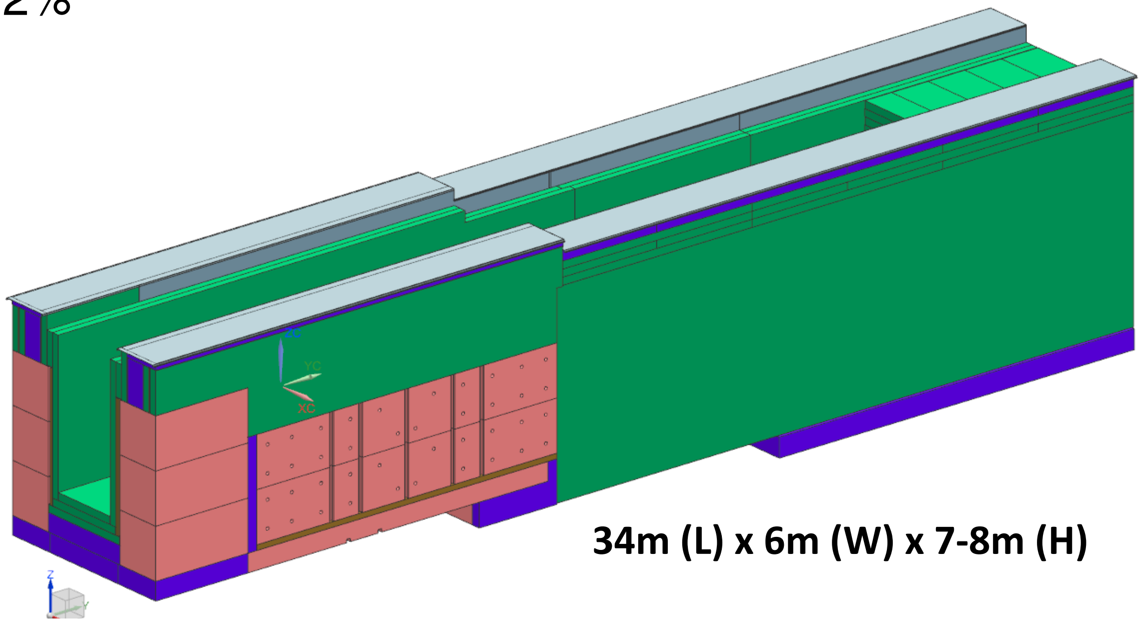
- CCM Chicago Cyclotron Magnet: 18%
- CDF Muon Wall: 4%
- Railhead steel: 3%

Purchase:

- CCSS (Continuous Cast Salvage Steel): 58%
- S-2 shielding blue-blocks: 12%
- Construction steel: 4%

37% is on-site or recycled steel

Shielding steel is stacked in a staggered and interlocking fashion so there are no line of-sight cracks through the steel shielding pile. Vertical gaps between pieces are filled with steel shim stock to the required maximum gap size of ~¼”



34m (L) x 6m (W) x 7-8m (H)

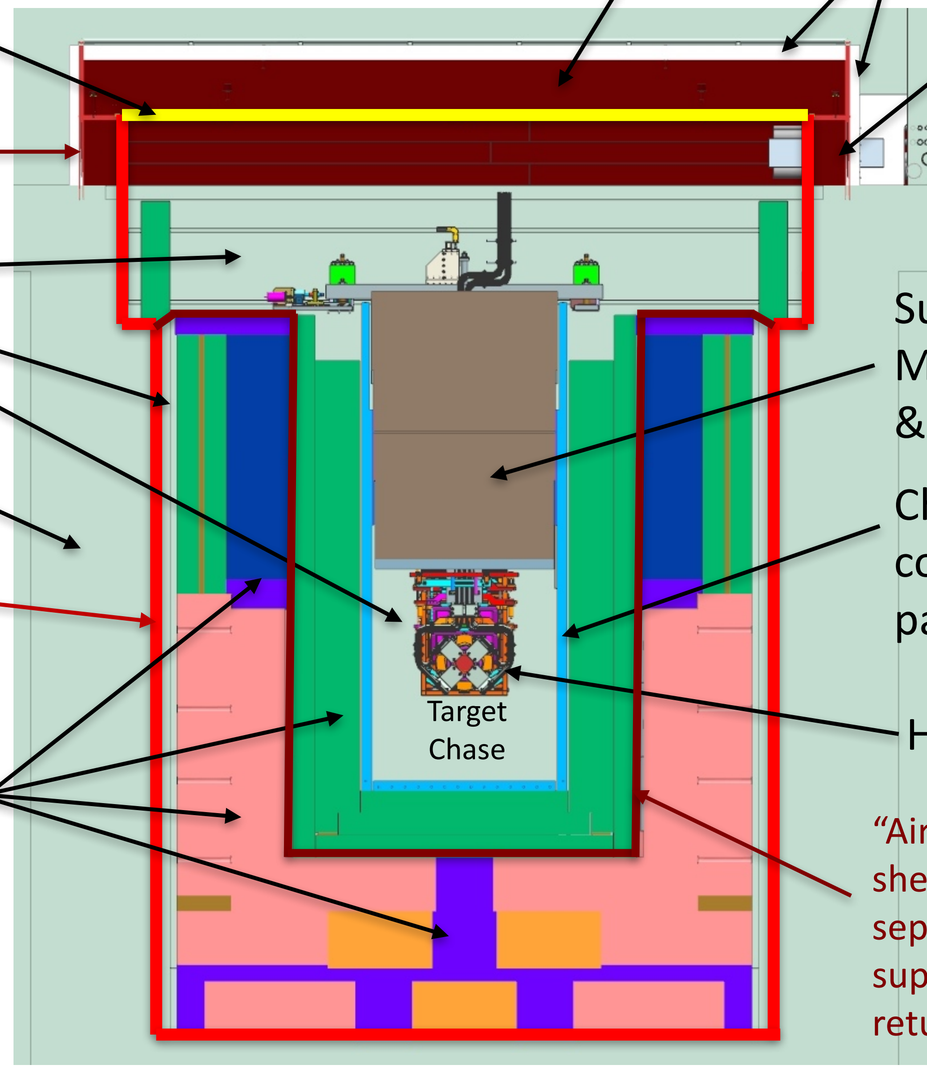
Requirements for inert gas (N_2) in the Target Shield Pile

- A much better sealed system (including N_2 handling unit) with a maximum allowable leak rate of ~7 cfm (compared to 266 cfm for air) due to radionuclide mitigation (mainly ^{11}C). Leak rate break up: 2 cfm for hatch cover system and 5 cfm for N_2 handling unit.
  - Requires leak-tight barrier inside the concrete shielding pit that also needs to seal around the DS decay pipe snout and US window opening. Barrier will not be accessible for repair and needs to last the lifetime of experiment.
- System will need to operate at 1-3 psig positive pressure range due to beam heating of air, barometric pressure changes due to weather, and pressure drop across the fan. Positive pressure is also desired to prevent air/oxygen from leaking in.
  - Structural integrity of ductwork, air handling unit, and chase containment volume need to be all addressed for higher design pressure of ~5 psig.

Requirements for inert gas (N_2) in Target Shield Pile - Contd.

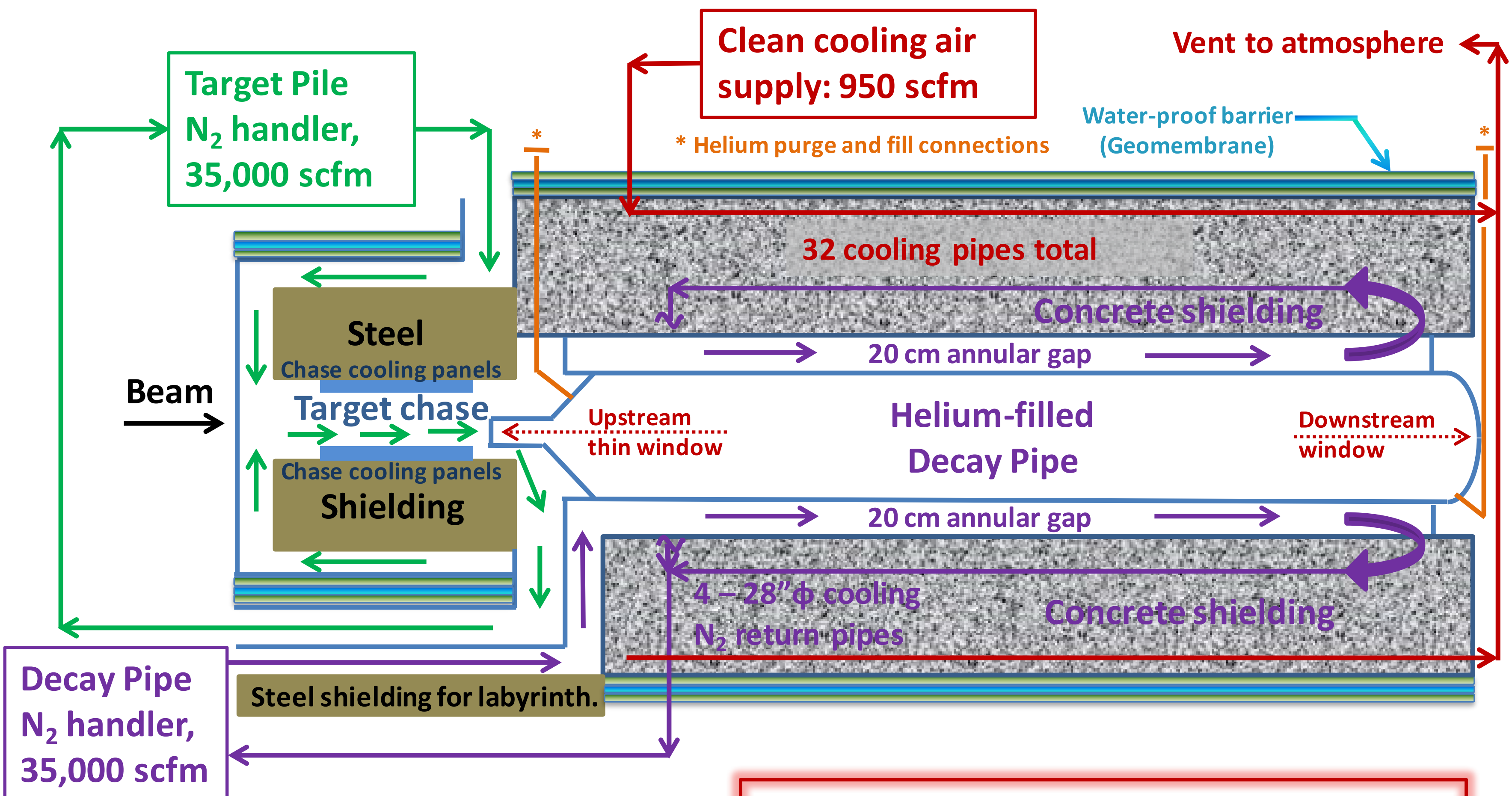
- Robust and repeatable leak-tight seals at all access points (such as hatch covers, and feedthroughs for the stripline & utility penetrations).
  - Ability to leak check the seals and repair/replace when needed.
  - Ease of operation during component change-outs (i.e. easy and efficient way to open and close the hatch-covers and re-seal the chase volume)
- Modular (flexible) design that allows for different component (target-horn) configurations in the future.
- Leak tight nitrogen fill/purge and monitoring system plus associated ODH considerations.

Target Station – Leak Tight Barrier System



N_2 flows upstream through the top and side passages and returns downstream through the chase. Some N_2 flows through the gaps in T-blocks and bulk steel shielding.

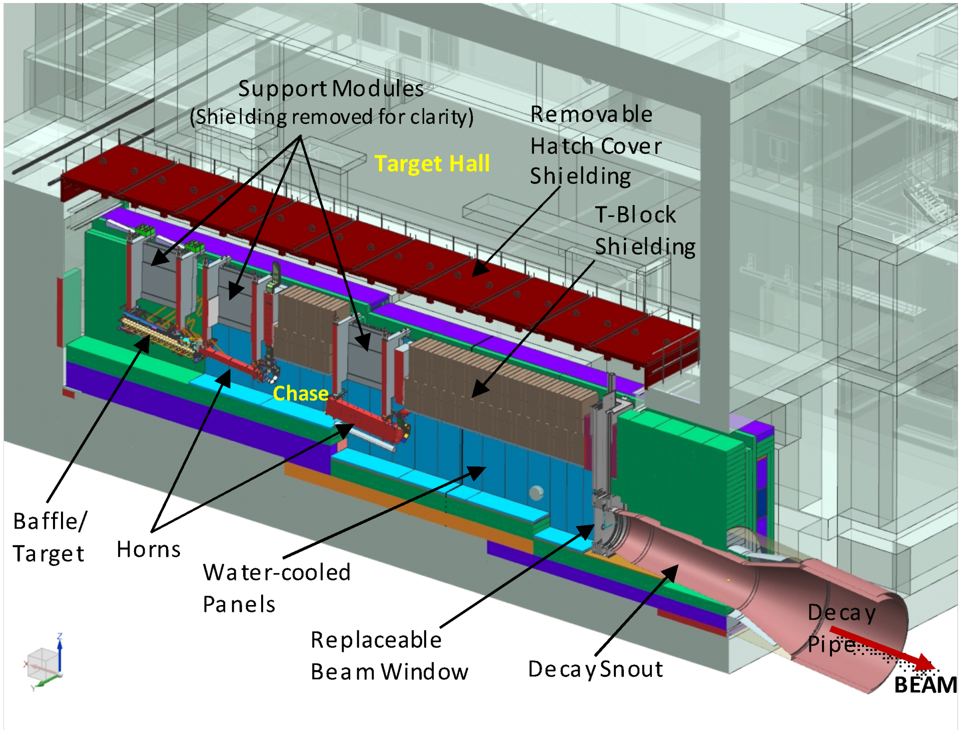
Target Shield Pile Gas Cooling Schematic



NOTE: The target pile N_2 cooling system and the decay pipe N_2 cooling system are two separate systems.

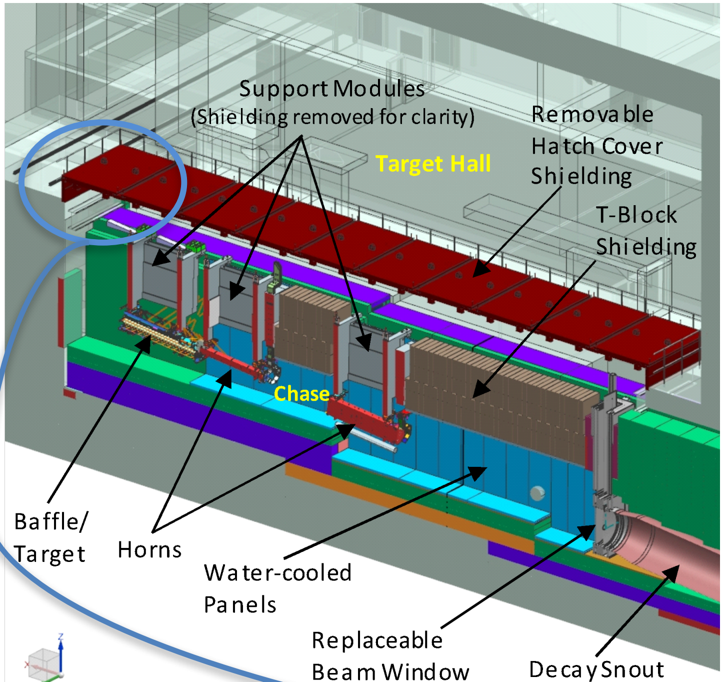
N_2 design – Hatch Cover Sealing System Conceptual Design

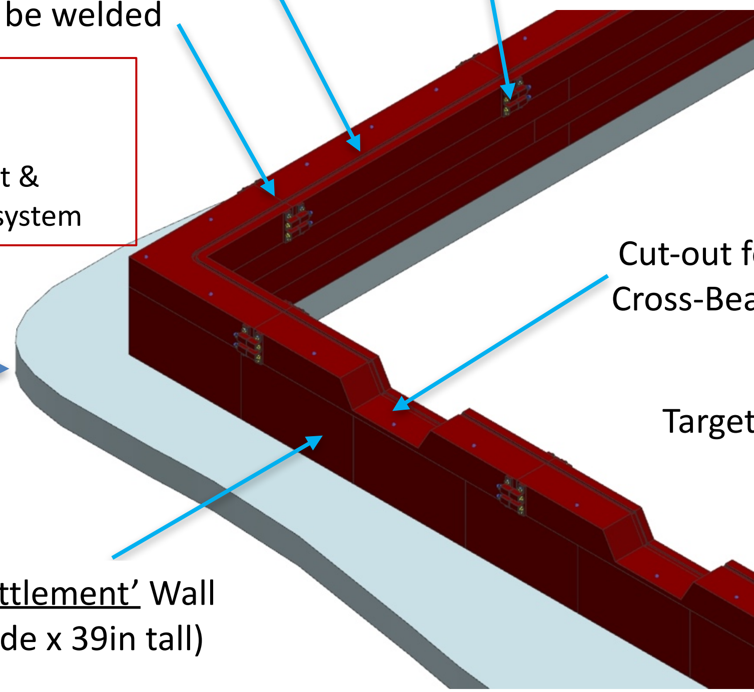
- 10 removable hatch cover plates (26.5 ft x 9.5 ft x 4 inch thick)
- EPDM O-ring seal (similar to J-PARC design which has helium in target chase)
- Removable cross-beams at the seams
- Hatch cover system needs to seal down to less than 2 cfm leak rate.



Hatch Opening:
23.5 ft x 98 ft [7.1m x 30m]

N_2 design – Hatch Cover Seal Conceptual Design



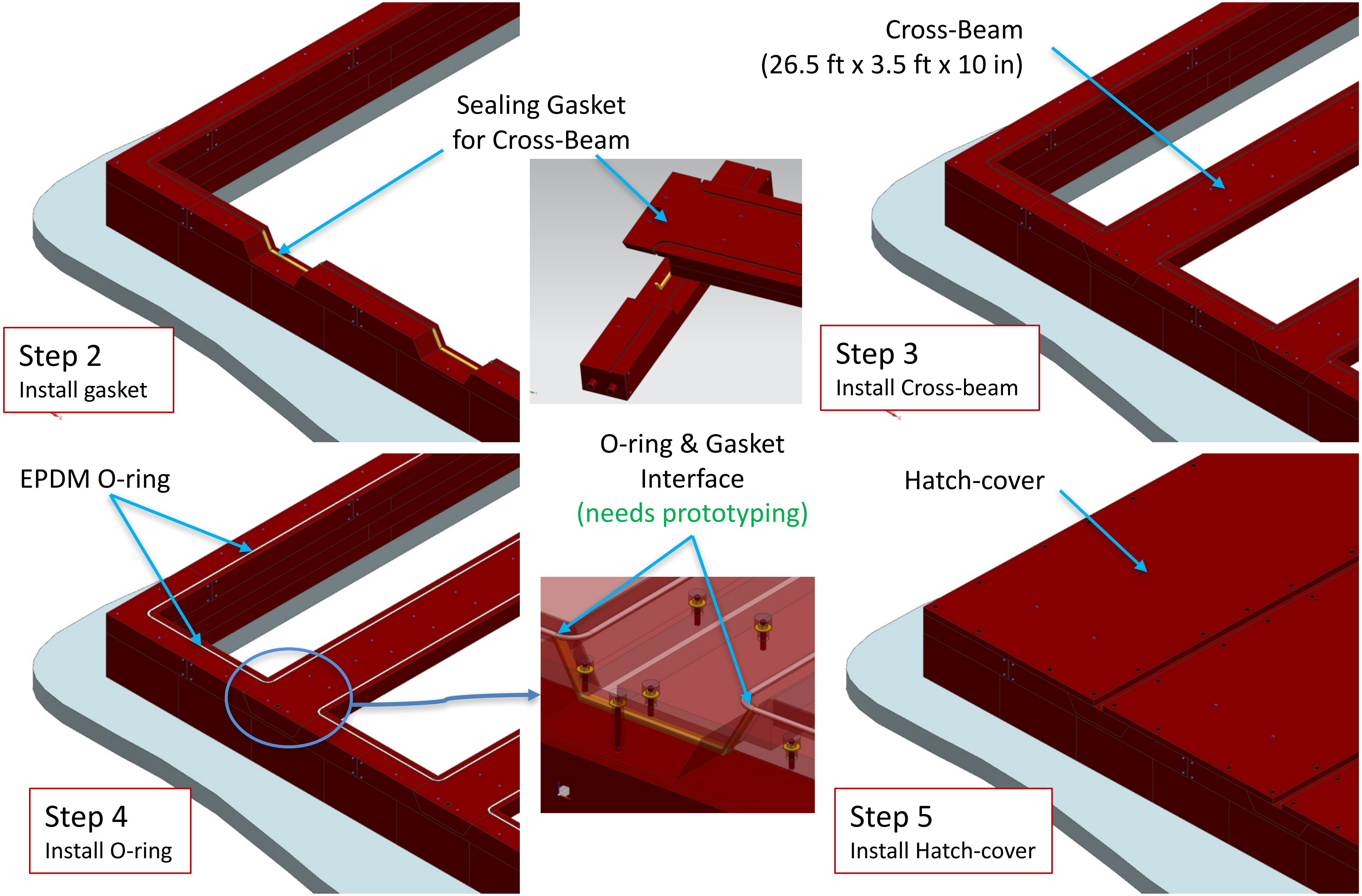


Step 1
Assemble
Battlement &
Top Plate system

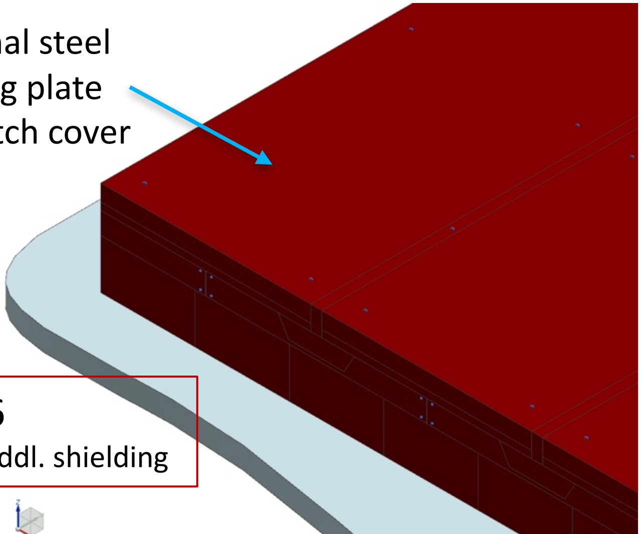
Some design challenges:

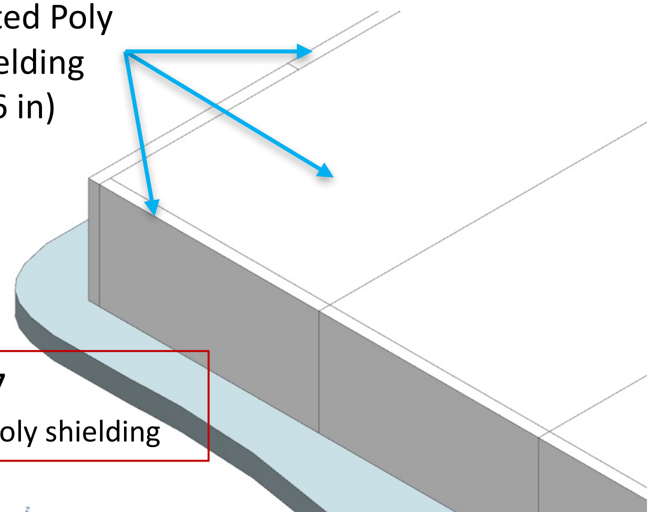
1. **Leak-tightness at the cross-beam and top-plate interface (T-junction of O-ring and gasket).**
2. **Alignment and assembly of the top plates. Plus overall alignment and constructability of entire system (very large structure) to the desired tolerance requirements.**
3. **Significant machining cost of top plates and hatch cover plates.**

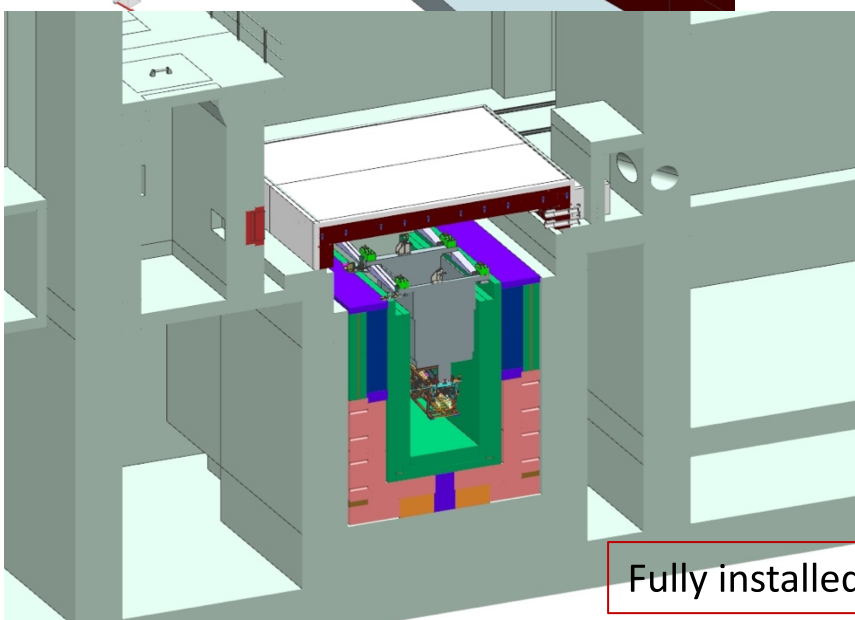
N_2 design – Hatch Cover Seal Conceptual Design

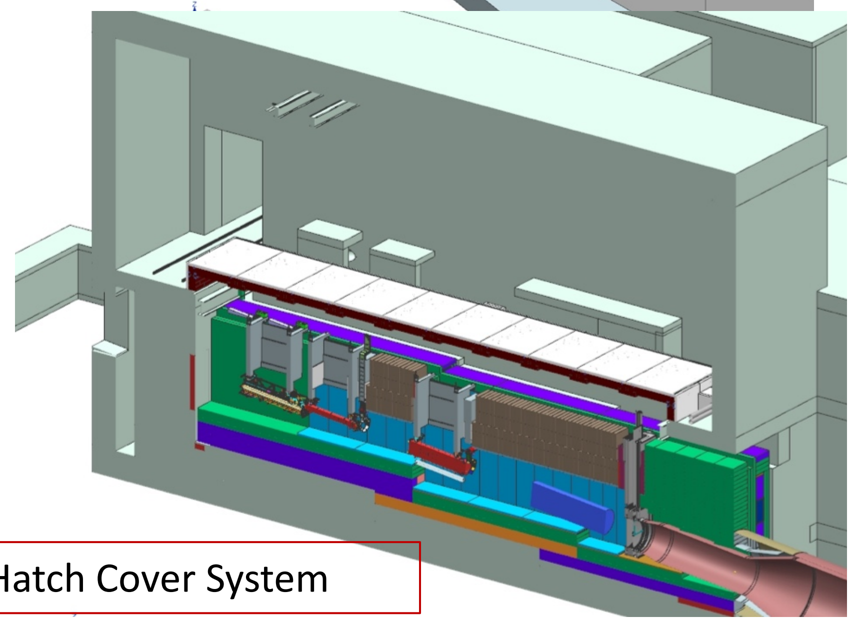


N_2 design – Hatch Cover Seal Conceptual Design



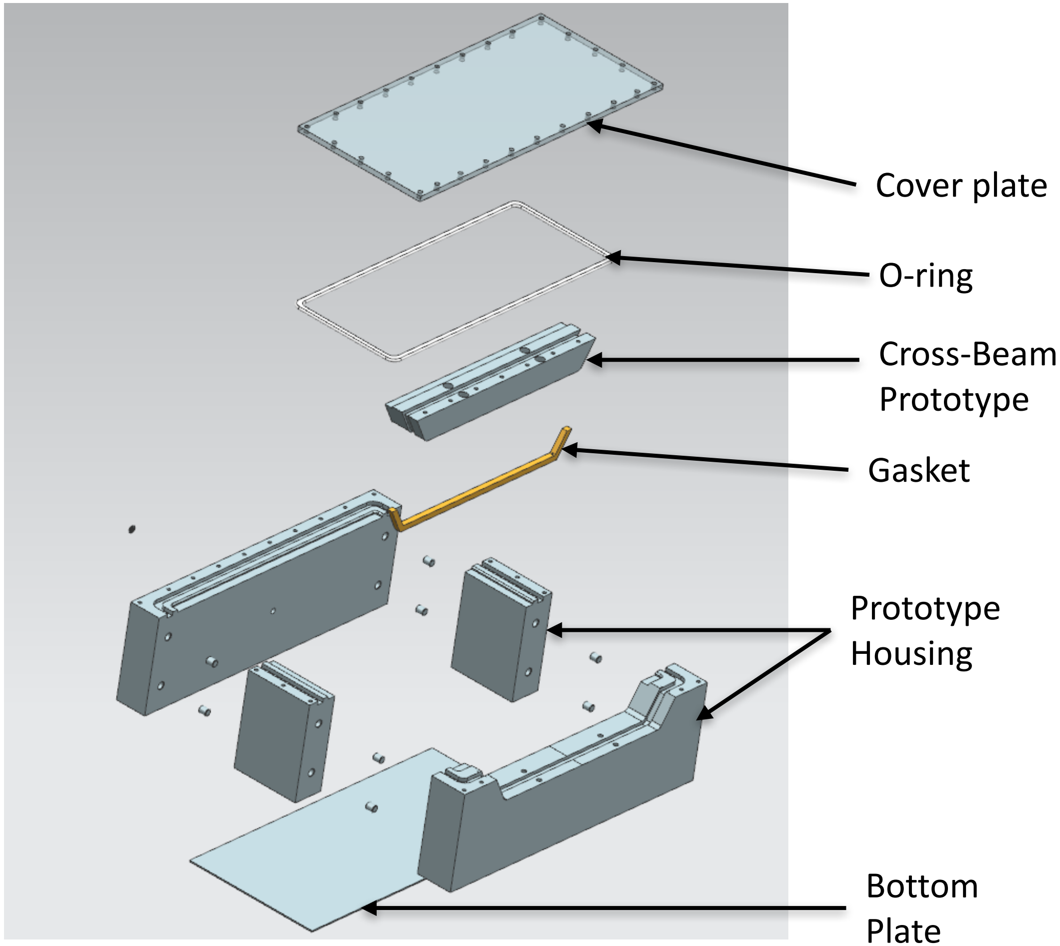


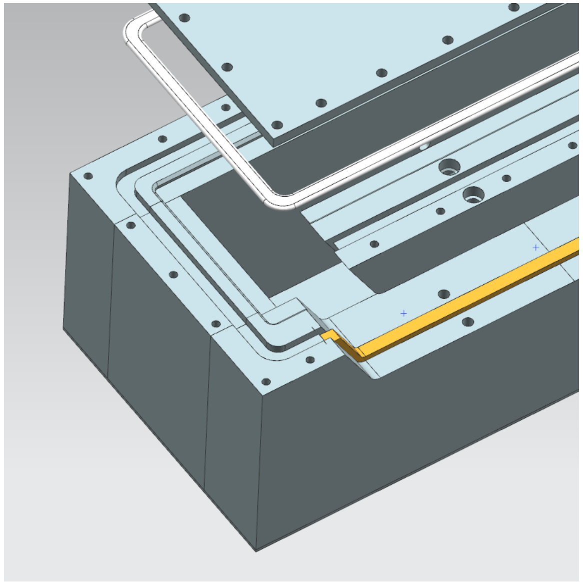


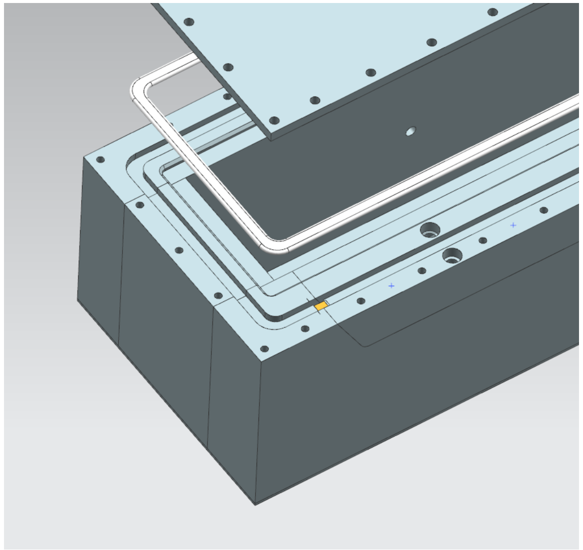


Fully installed Hatch Cover System

N_2 design – Hatch Cover Seal Prototype Concept

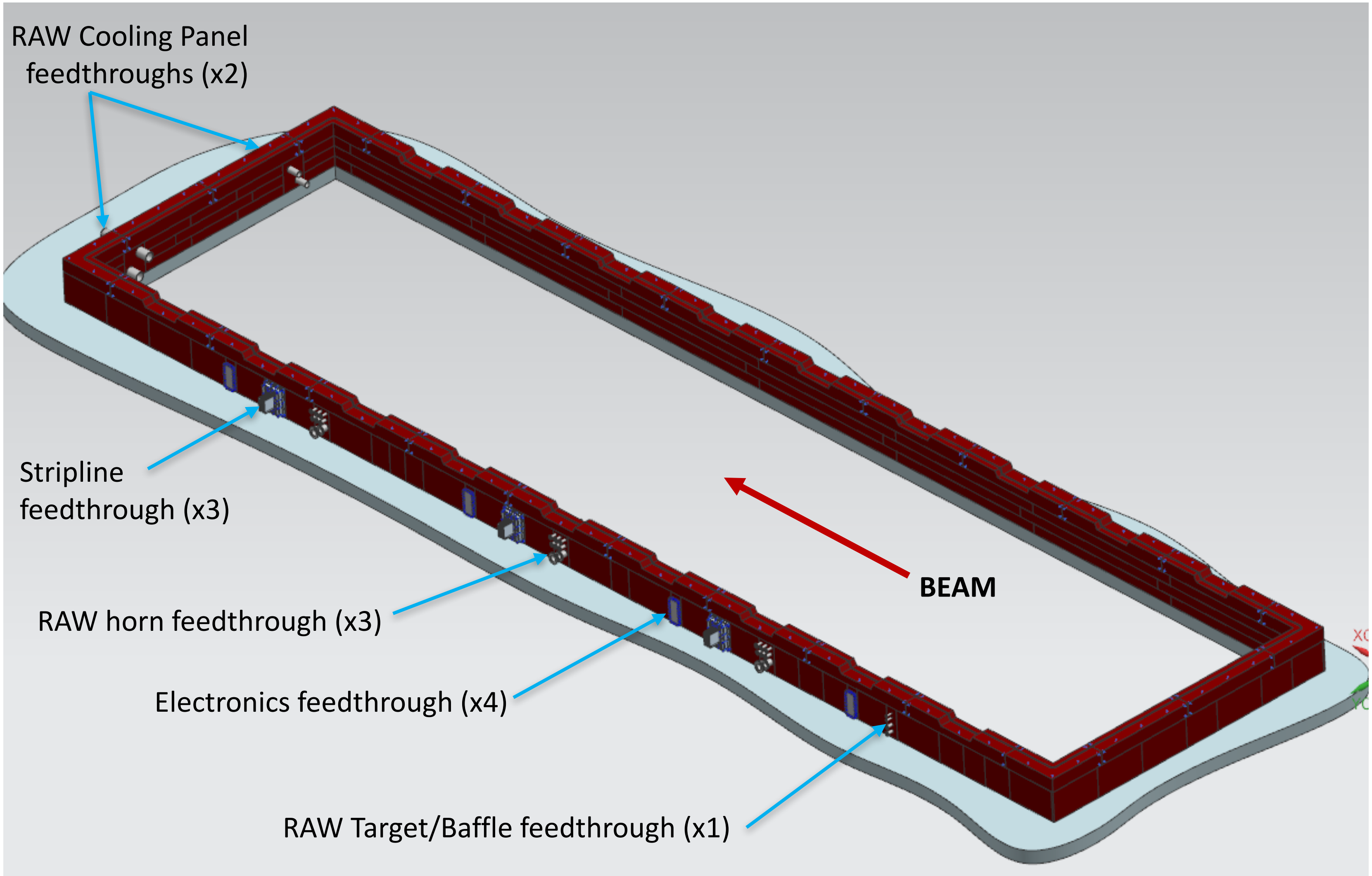






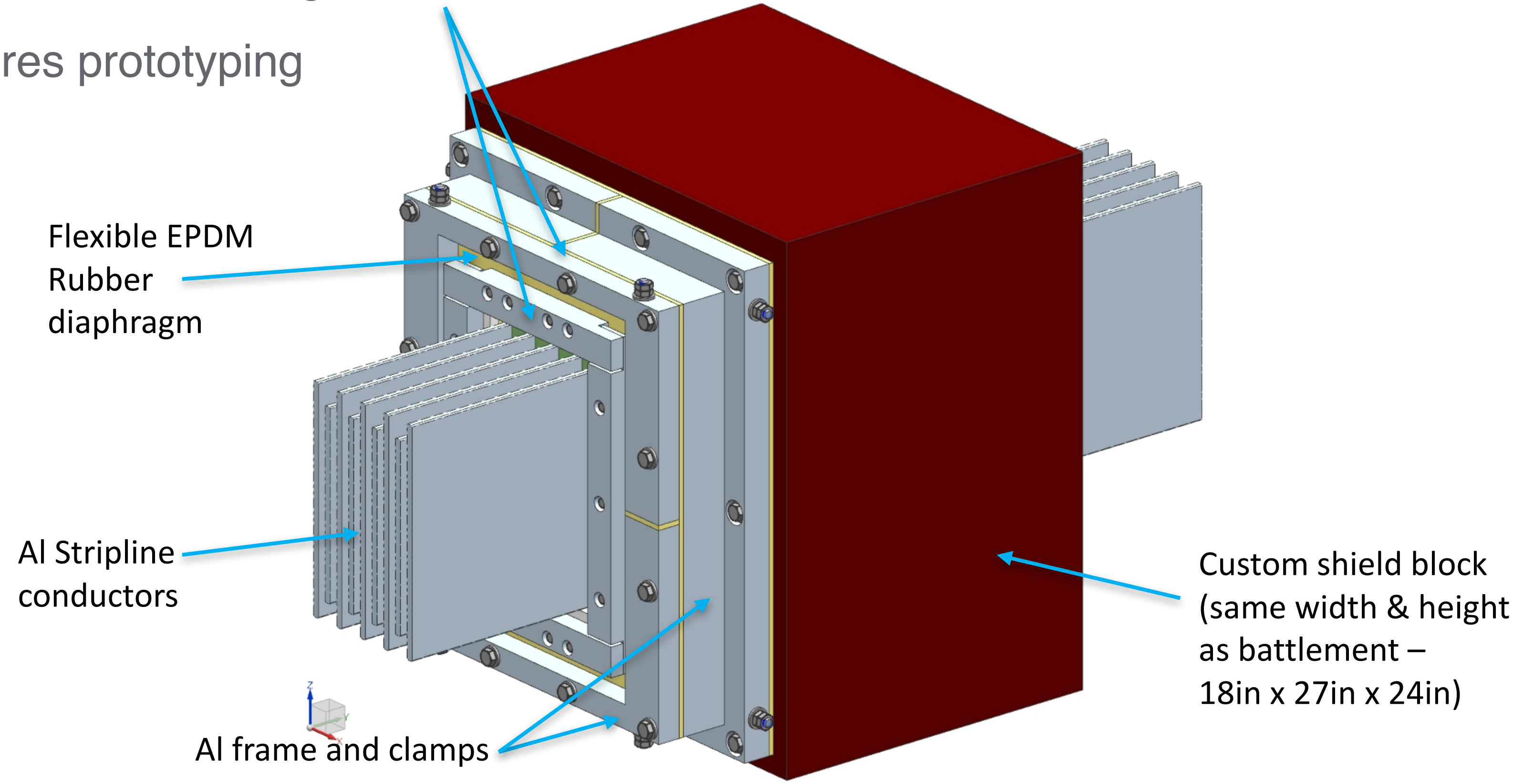
Might need to develop a larger, near full scale prototype for the Cross-Beam and O-ring seal system

N_2 design – Battlement showing Feedthrough Locations

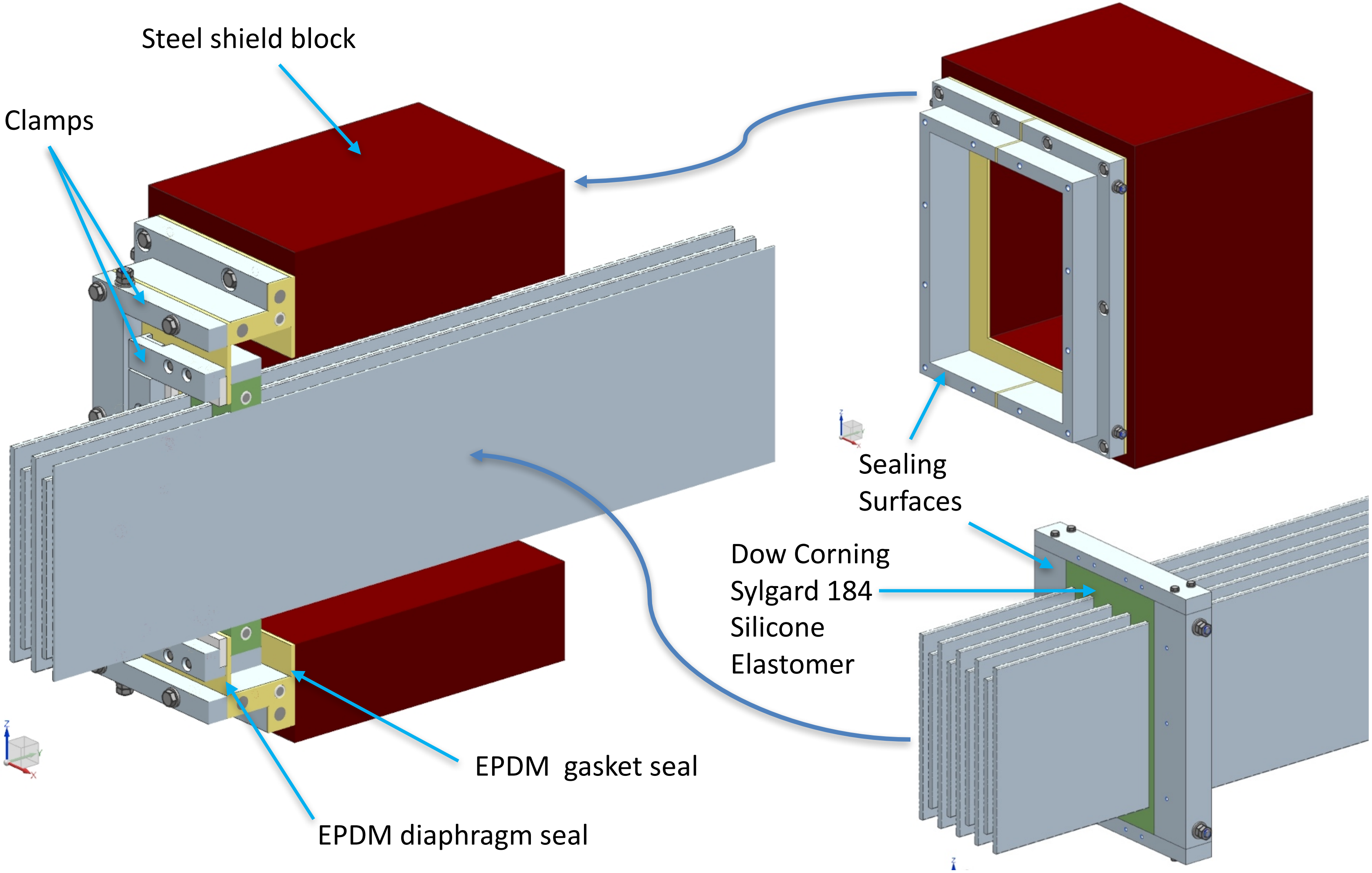


N_2 design – Stripline Feedthrough Conceptual Design

- Similar to the NuMI/NOvA design, custom shield block fits in an opening in the battlement (the sheet-metal air barrier seals around the custom shield block)
- Bolted flange seal design using flexible diaphragm (EPDM rubber) to seal between the 2 sealing surfaces
- Requires prototyping

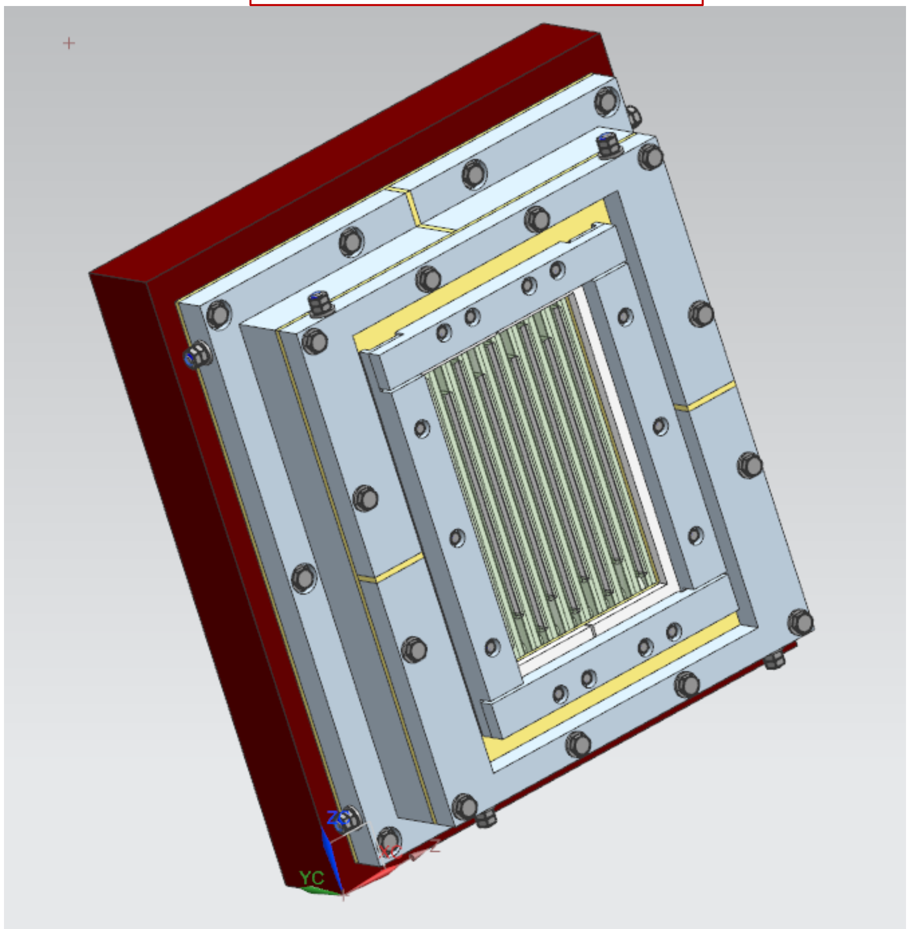


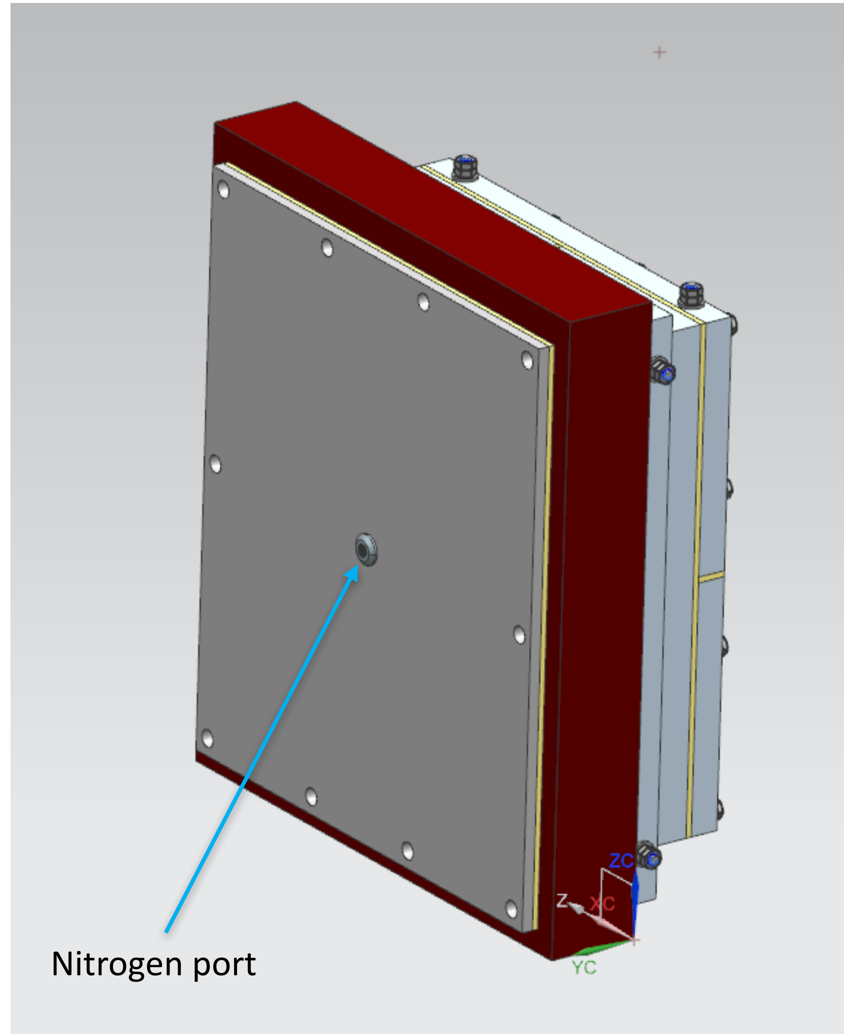
N_2 design – Stripline Feedthrough Conceptual Design contd.



N_2 design – Stripline Feedthrough Prototype Concept

Full Scale Prototype

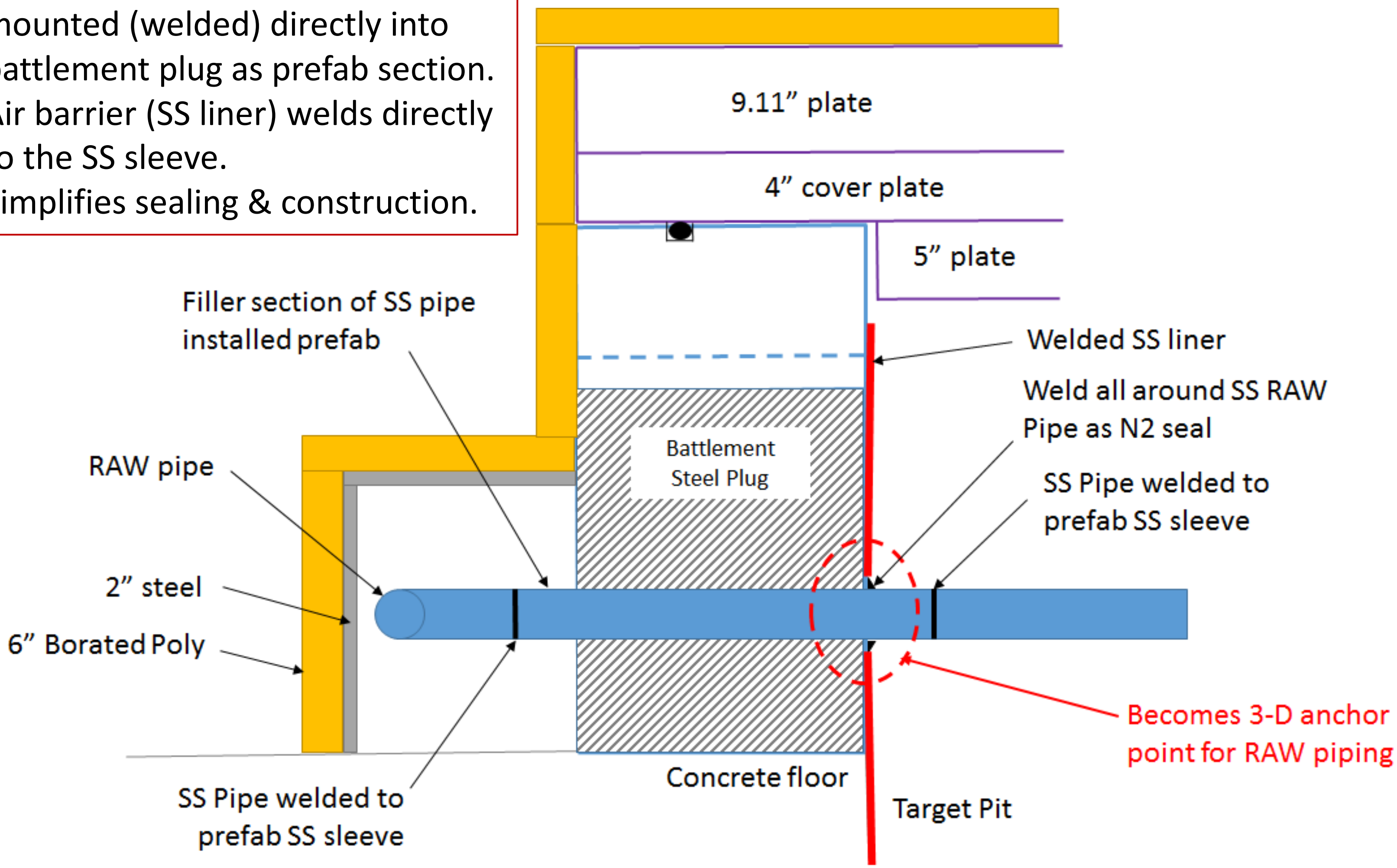




N_2 design – RAW Feedthrough Design Concept – Single Pipe

Single (large) RAW pipe:

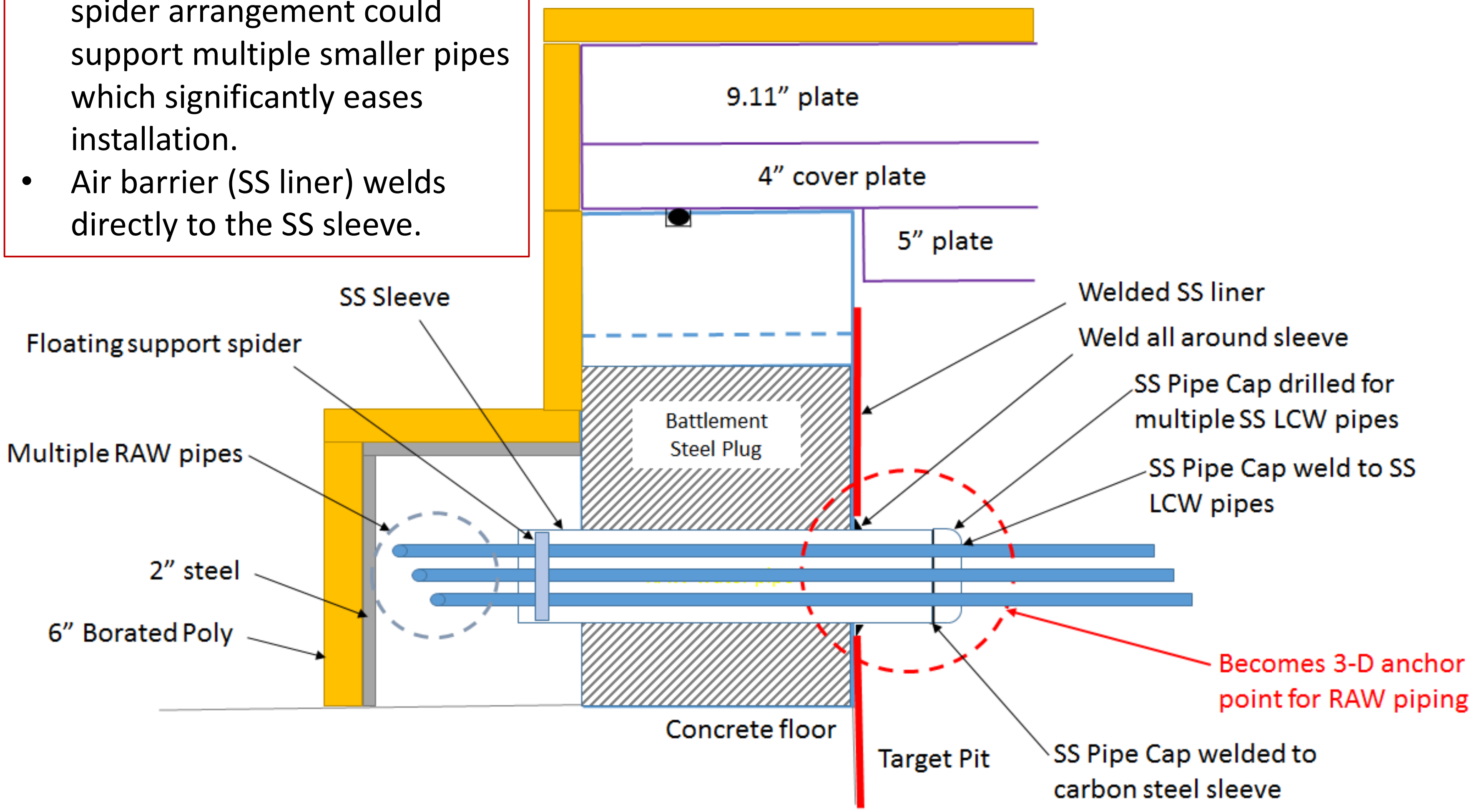
- SS Schedule 80 RAW pipe mounted (welded) directly into battlement plug as prefab section.
- Air barrier (SS liner) welds directly to the SS sleeve.
- Simplifies sealing & construction.



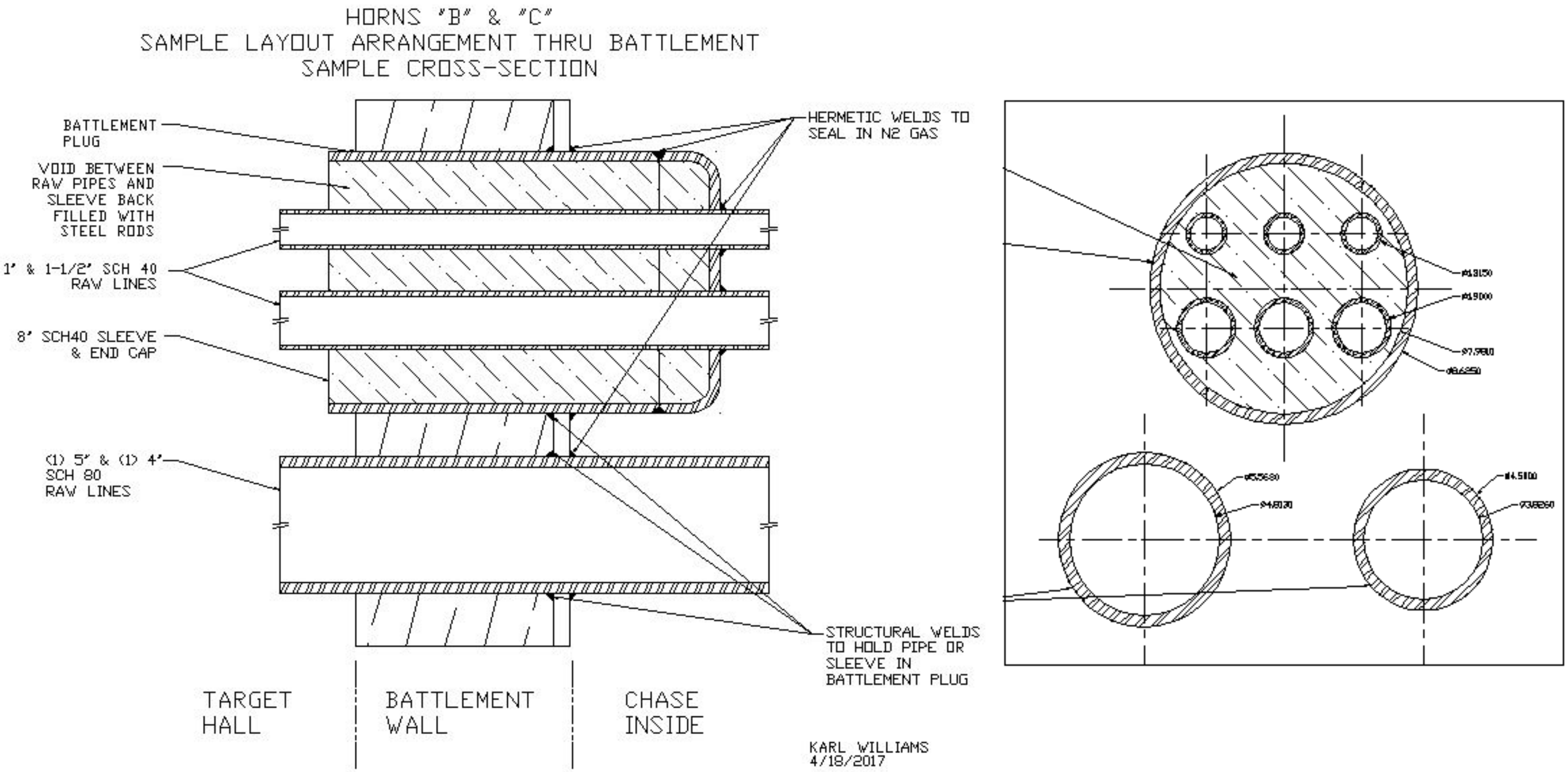
N_2 design – RAW Feedthrough Design Concept – Multiple Pipe

Multiple (small) RAW Pipes:

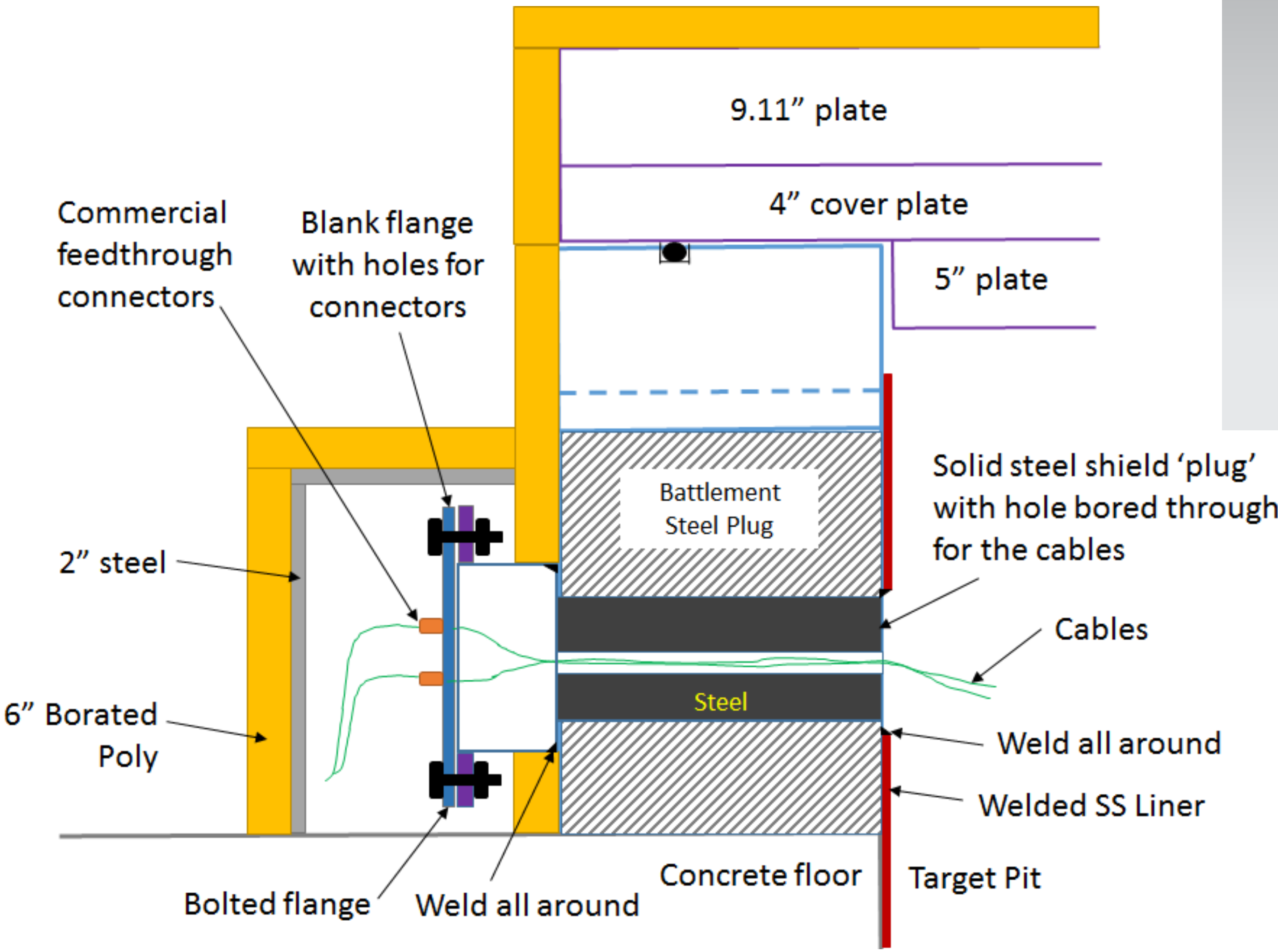
- One sleeve, end cap, and spider arrangement could support multiple smaller pipes which significantly eases installation.
- Air barrier (SS liner) welds directly to the SS sleeve.

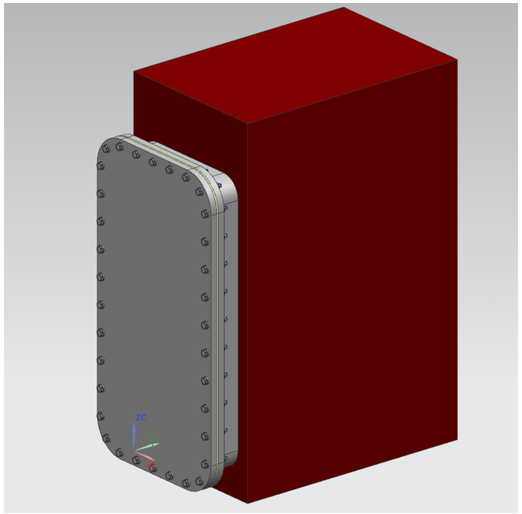


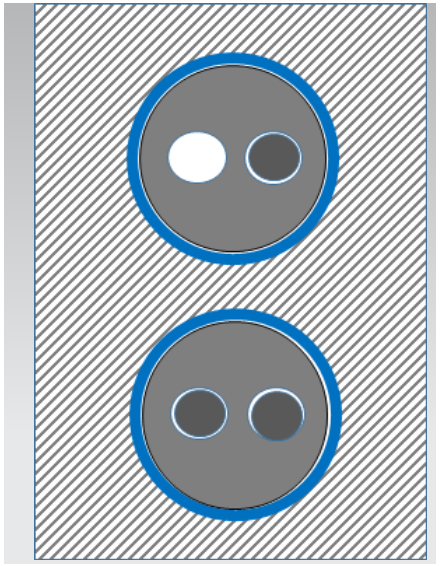
N_2 design – RAW Feedthrough Design Concept



N_2 design – Electronics Feedthrough Conceptual Design

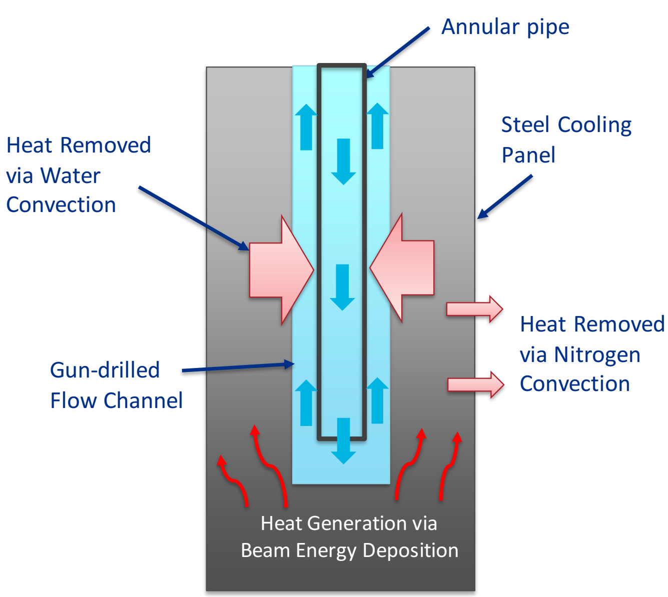




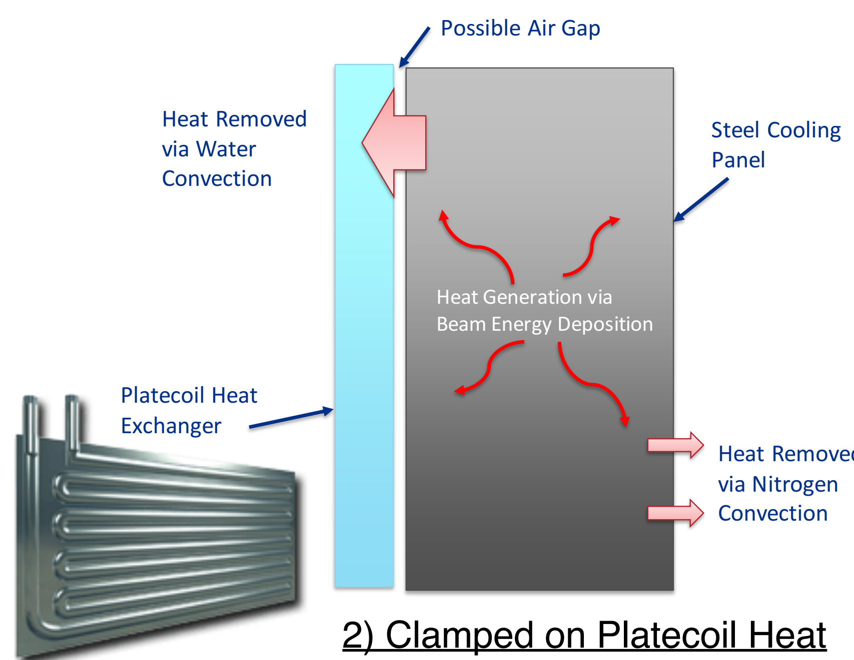


Cooling Panel Design

- U-Shape Cooling Panels are 4 inch (10 cm) thick carbon steel. Panels are replaceable.
- Two cooling option being considered:
  - 1) Gun drilled water cooling channels – limitation on how deep one can gun drill.
  - 2) Clamped on commercially available Platecoil Heat Exchangers (stainless steel)
- Plan is to further investigate 2nd option – simpler and more cost effective.

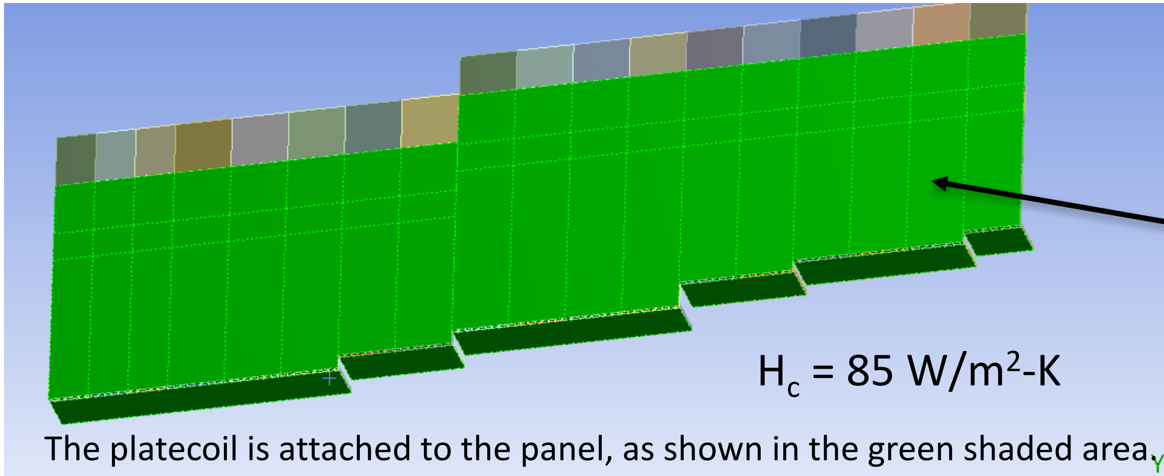


1) Gun-drilled Water Channels in the 4 inch Steel Cooling Panel

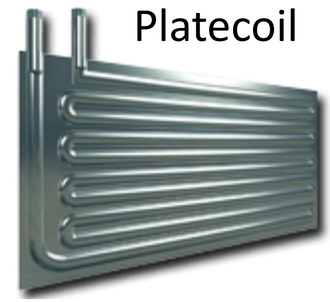


2) Clamped on Platecoil Heat Exchanger

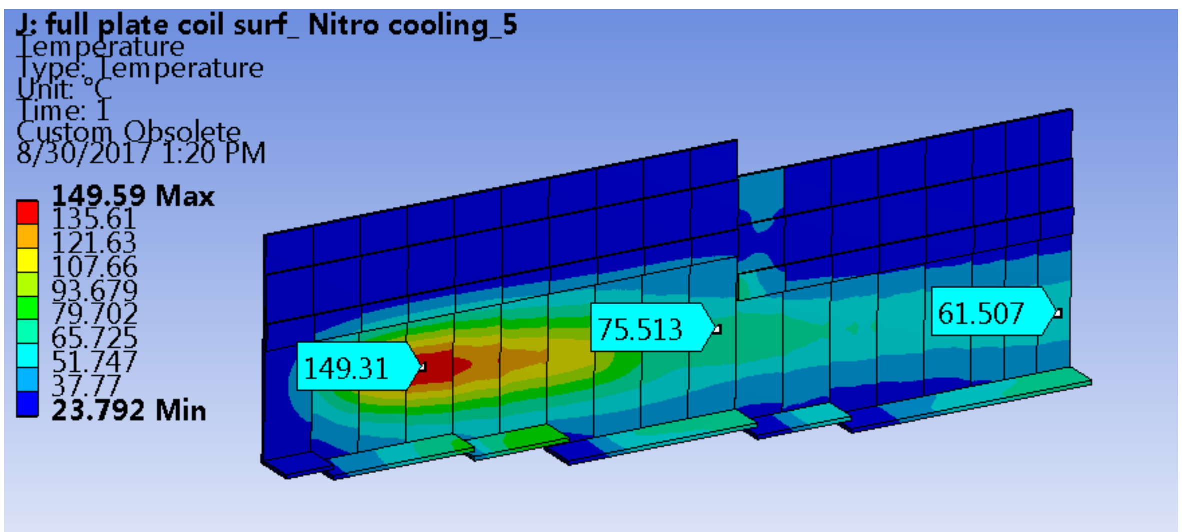
Cooling Panel Design – FEA at 2.4 MW Optimized Configuration



U shape panel half structure. 542 KW heat is deposited into the cooling panels.



Platecoil



Results:

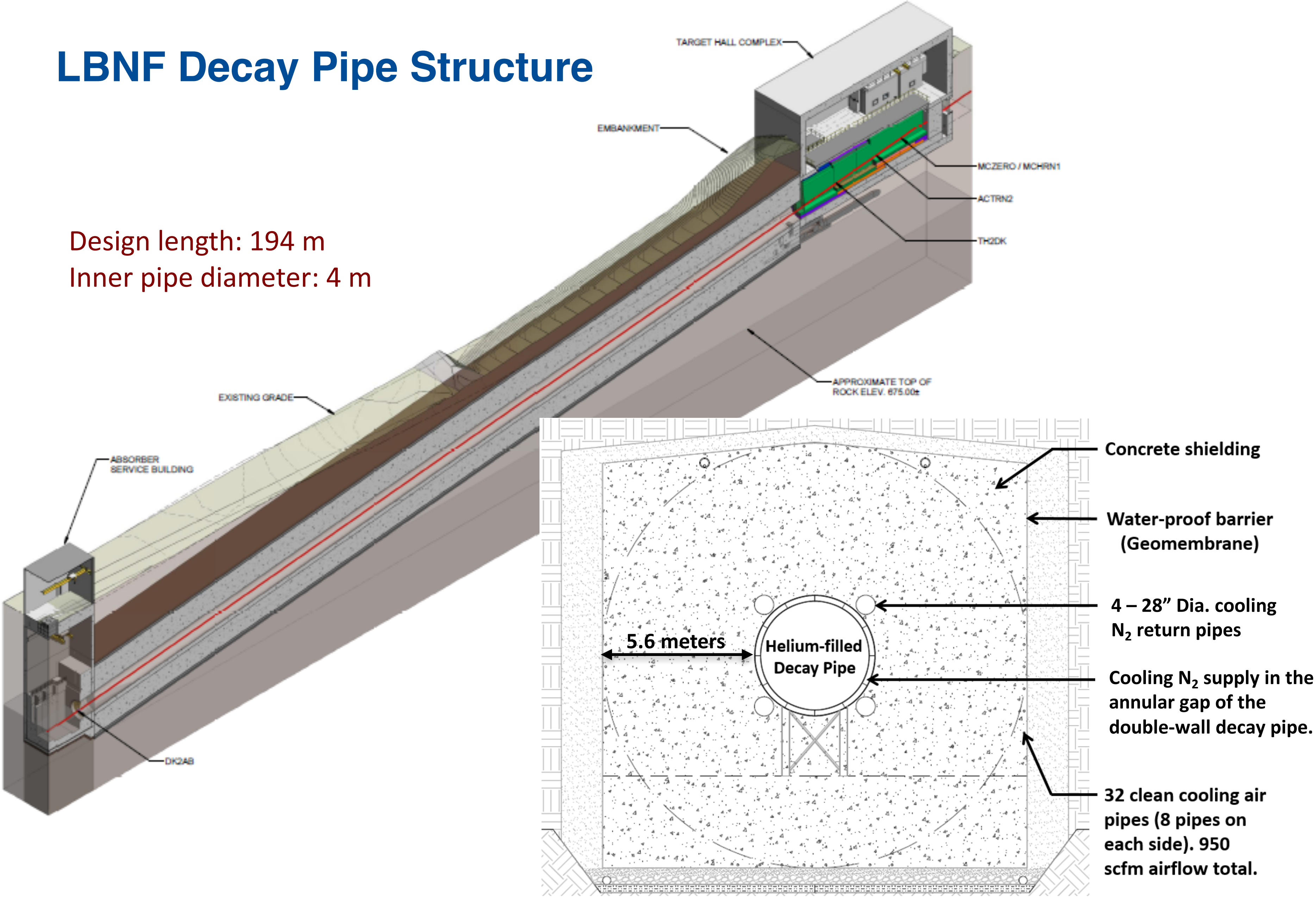
T_{max} = 149.6°C

~96% of the heat is extracted by the Platecoil and ~4% by the N_2 gas cooling.

Decay Pipe Design (*Conceptual*)

LBNF Decay Pipe Structure

Design length: 194 m
Inner pipe diameter: 4 m



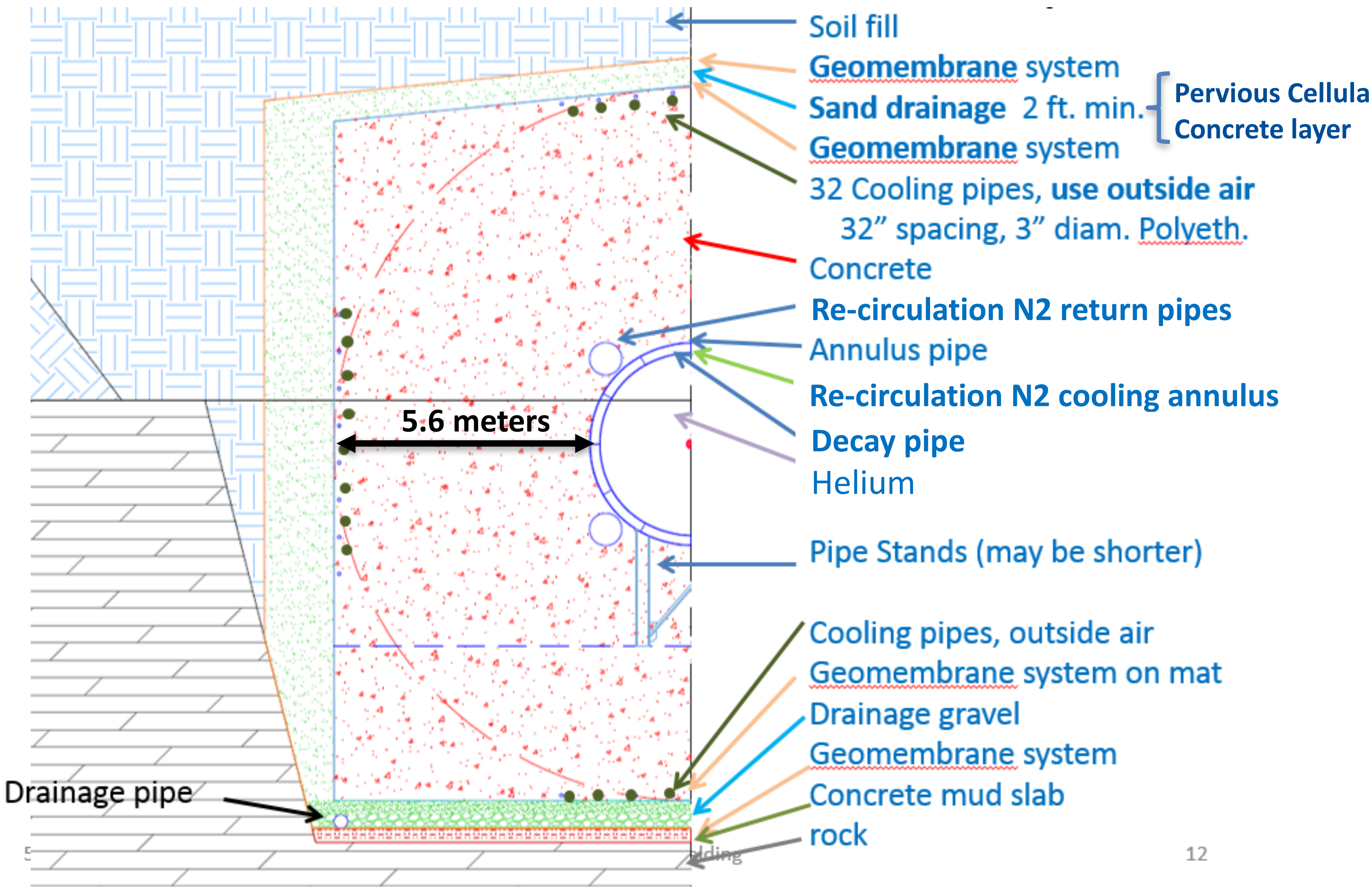
Decay Pipe Overview

- Located directly downstream of the Target Shield Pile.
- Designed for 2.4 MW beam power – the decay pipe and its shielding are built underground and their size cannot be modified or upgraded after completion.
- Helium filled and nitrogen cooled (cooling happens through an annular duct surrounding the decay pipe) – nitrogen mitigates any corrosion issues.
- Concrete radiation shielding surrounds the decay pipe to keep the groundwater activation levels (over the operating life of LBNF) below the standard detection levels. 2-3 feet of Pervious Cellular Concrete layer provides drainage outside the concrete shielding.
- Geomembrane system (multi-ply geosynthetic barrier) surrounds the decay-pipe concrete to act as a barrier for ground-water inflow.
  - Set of air-cooling pipes just inboard of the geosynthetic system keeps the geomembrane at low temperature to extend its lifetime (80 years)
  - The geo-membrane can tolerate a total of 10 Mrad; will not be radiation damaged over the life of the facility.

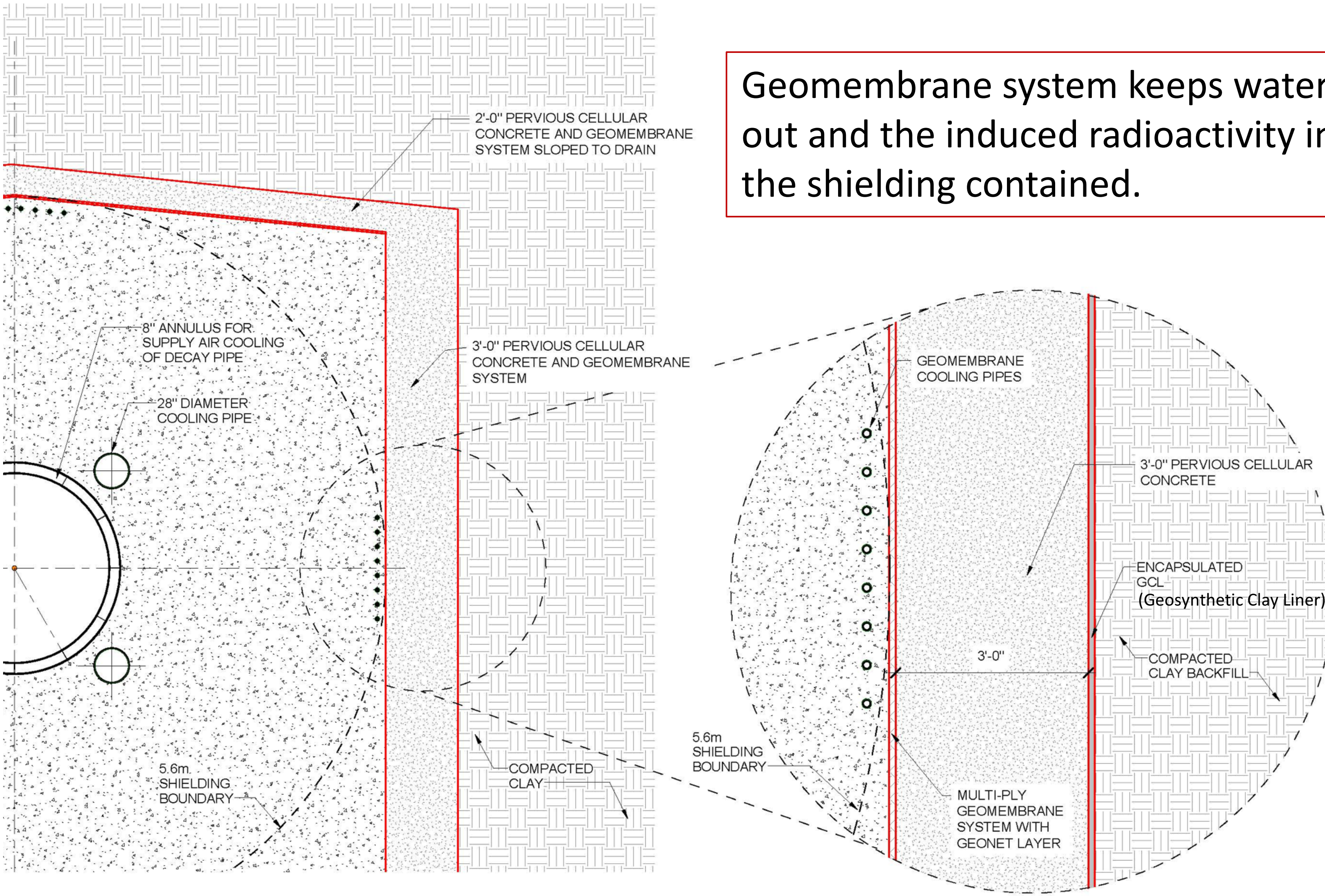
Decay Pipe Design Specifications

- 194 m long
- 4 m inside-diameter steel pipe installed concentrically in a 4.43 m inside diameter steel pipe; the annular gap between the pipes is 20 cm.
- Commercial-grade carbon steel pipes with wall thickness of 12.5 mm. External and internal corrosion protection.
- Spacers welded between the two pipes to maintain concentricity and to not interfere with the gas flow.
- Alignment accuracy maintained at 20 mm
- Helium at positive pressure (1.5 psig)
- Concrete radiation-shielding thickness of 5.6 m

Decay Pipe Design

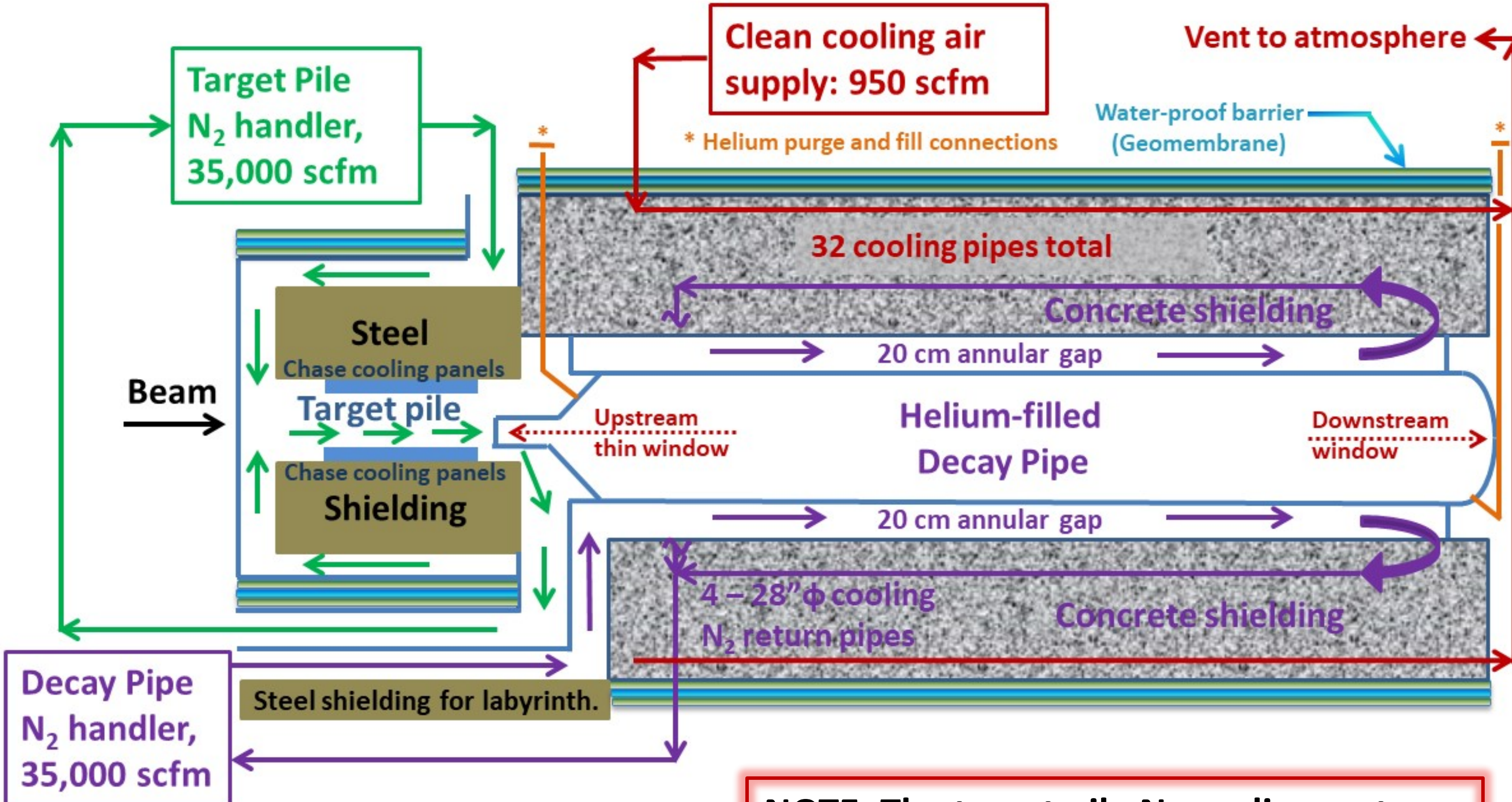


Decay Pipe Geomembrane System Design



Geomembrane system keeps water out and the induced radioactivity in the shielding contained.

Decay Pipe Gas Cooling Schematic

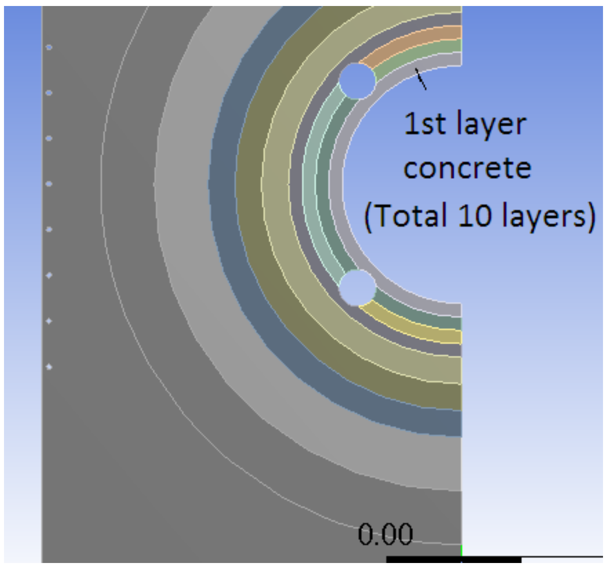


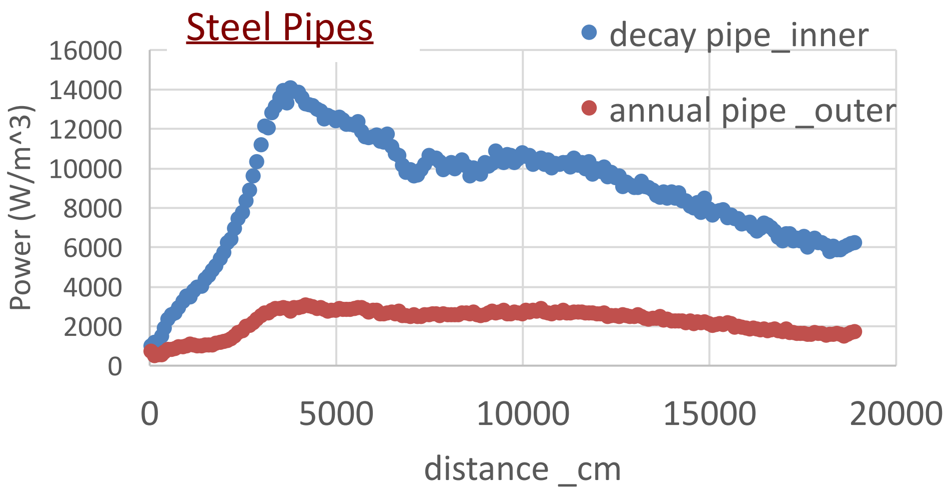
NOTE: The target pile N_2 cooling system and the decay pipe N_2 cooling system are two separate systems.

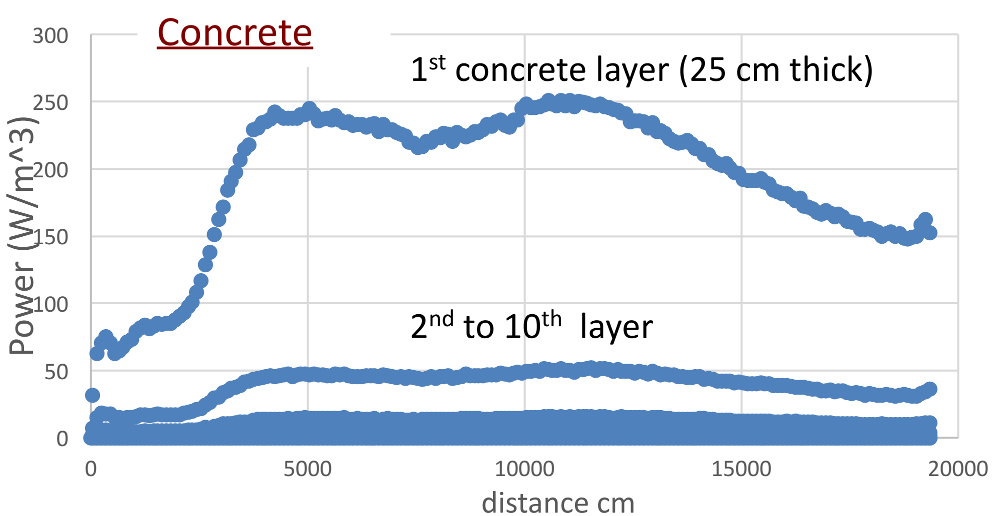
Decay Pipe Thermal & Structural FEA – Optimized Configuration

EDEP for the double steel pipe _(ref Dune-doc-3303-v2)

Energy Deposition at 2.4 MW



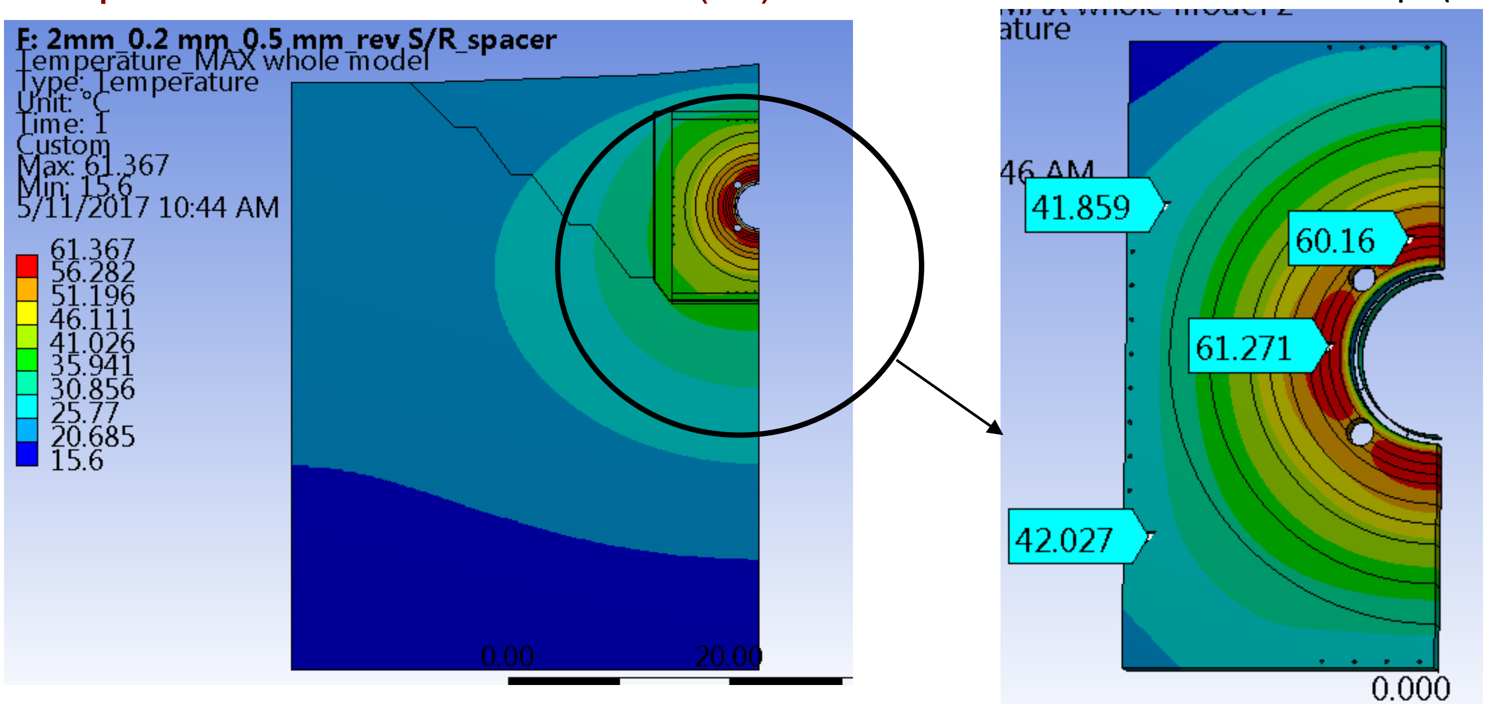




Decay Pipe Thermal & Structural FEA – Optimized Configuration

Temperature results for 2.4 MW (°C)

Maximum concrete temp. (°C)



- Thermal and stress analysis shows that all temperature and stresses are within allowable limits.
- Max. concrete temp. << 100°C; Max. inner geomembrane temp. << 45°C

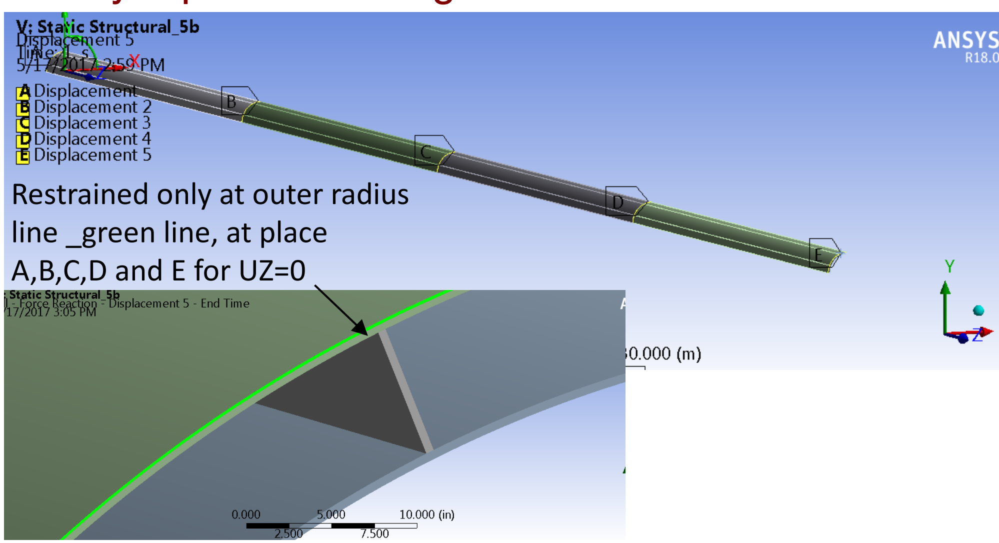
Decay Pipe Thermal & Structural FEA – Optimized Configuration

Decay Pipe Thermal Stress (2-D plain strain)

	Decay pipe	Annular pipe	28" pipe		
T final	46	38.9	57		
Tref	15	15	15		
ΔT _C	31	23.9	42		
α _ 1/C	1.20E-05	1.20E-05	1.20E-05		
E _psi	2.90E+07	2.90E+07	2.90E+07		
stress (ksi)	10.79	8.32	14.62		
FEA (ksi)	11.1	8.94	15.5	<<21.6 ksi=36*0.6 (A36)	
			or	<<30 ksi=50*0.6 (A50)	

The thermal stresses are low and acceptable

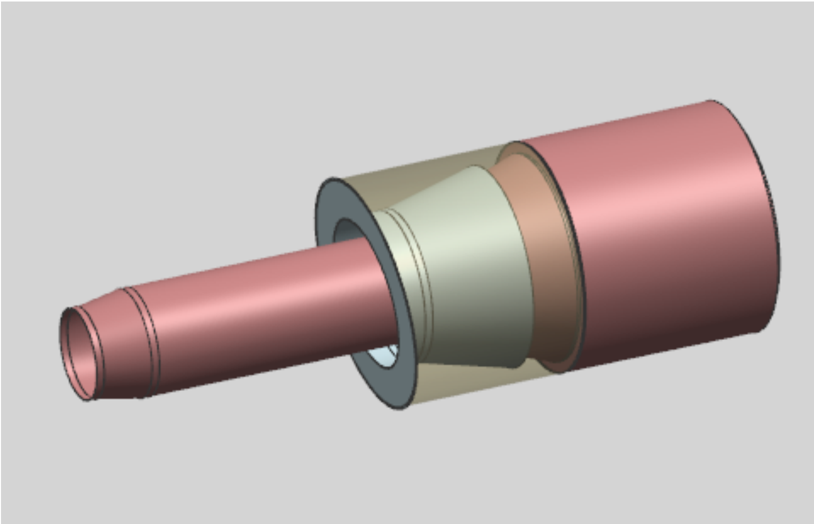
Decay Pipe Restraining Force

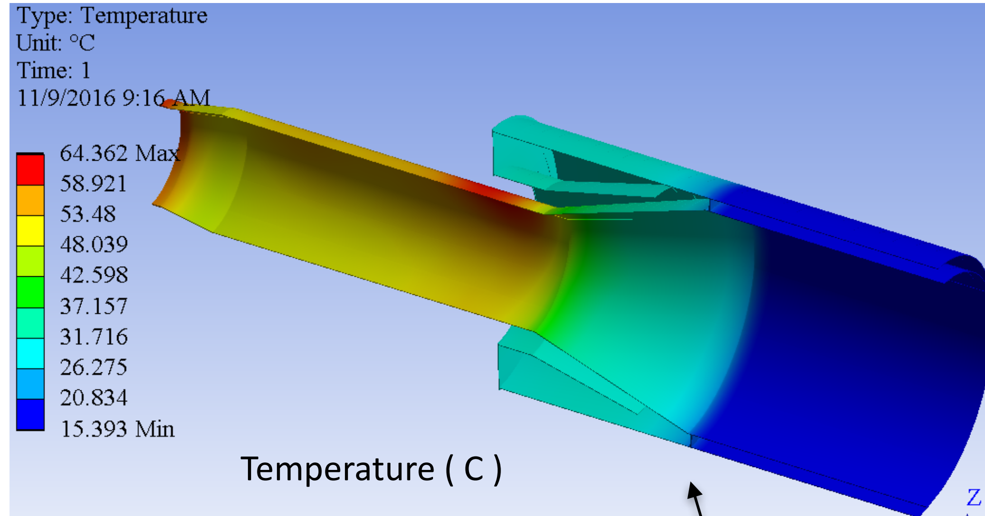


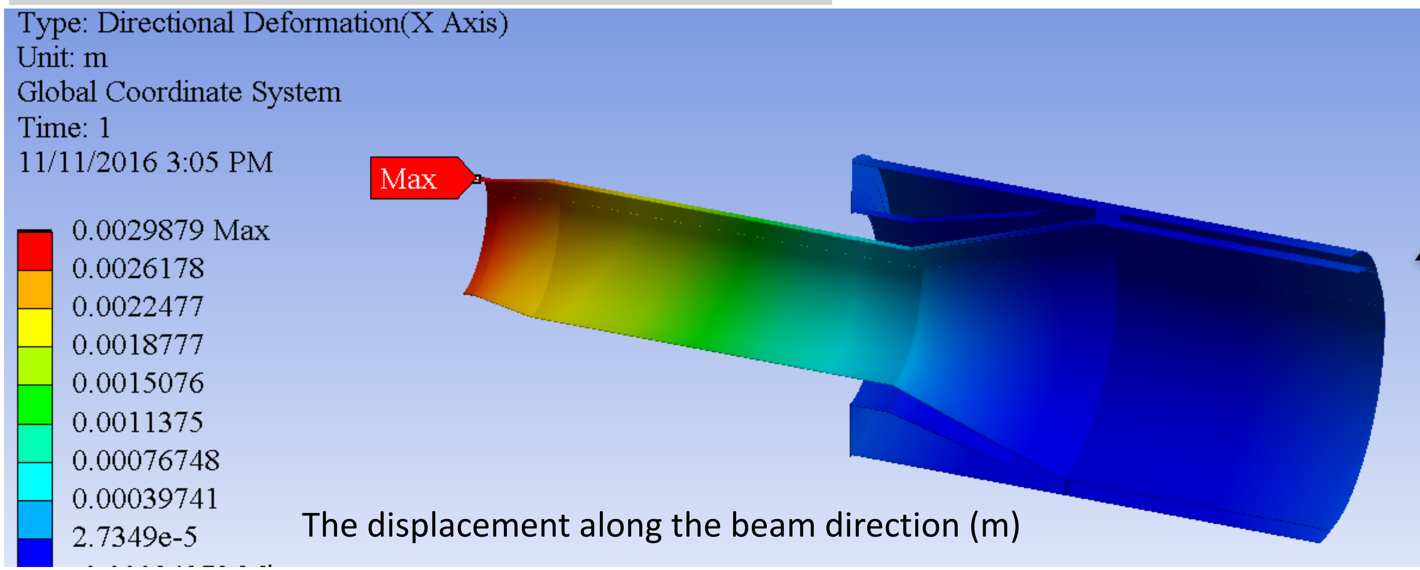
The total restraining force was calculated to be 3.85E06 Lbf

Assuming a 1 inch thick flange structure to constrain the force, the shear stress is calculated to be 7 ksi << 10,800 ksi (allowable for A36 steel, allowable for A50 steel is 30,000 ksi).
No issues in terms of stress.

Decay Pipe Snout Thermal FEA – Optimized Configuration 2.4 MW







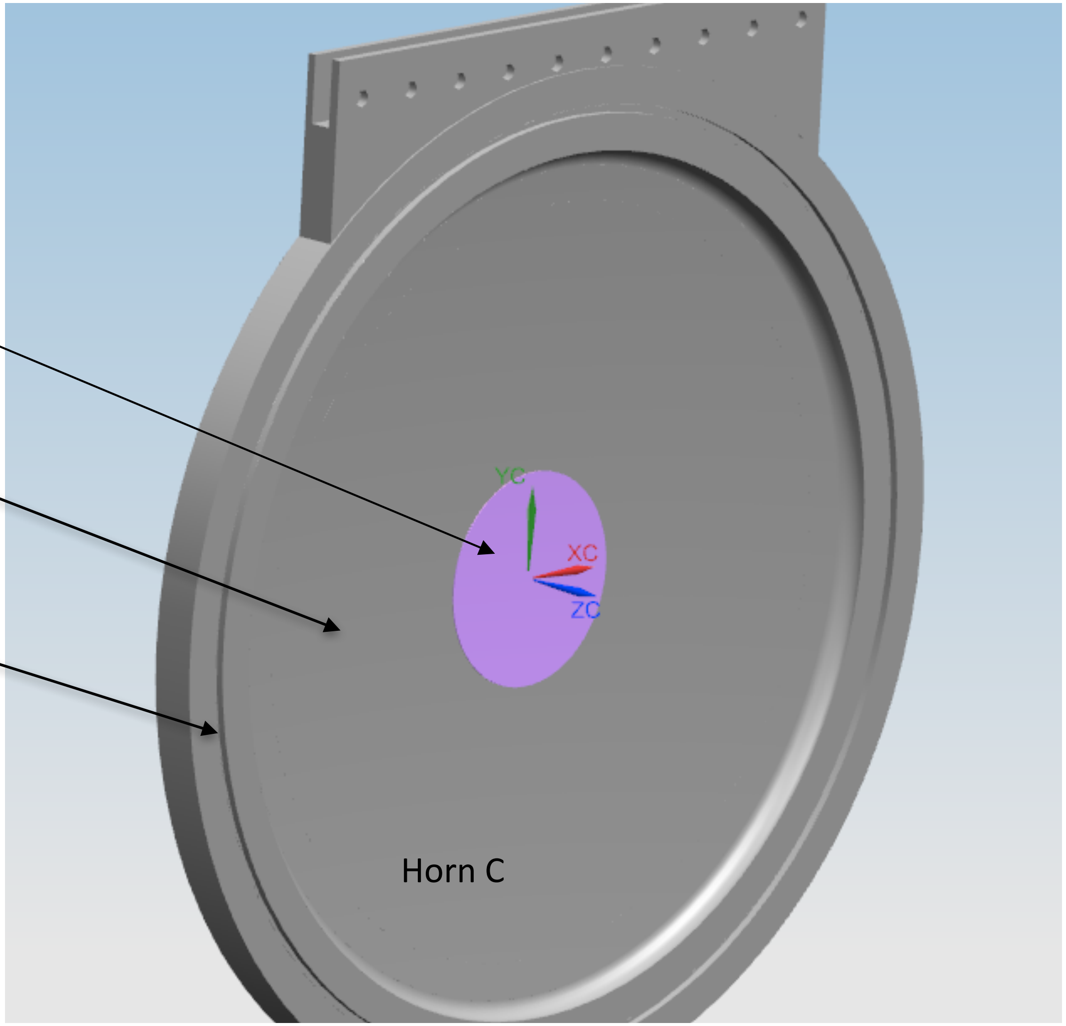
T_{max}= 64.4°C
D_{max}= 2.9 mm
Total heat= 10.4 KW

Decay Pipe US Window Membrane Weldment (Center Section)

Beryllium or AlBeMet center section

Anodized 6061 Al outer section

Commercial metal seal or an inflatable custom seal will occupy the groove.



Decay Pipe US Window Seal Mechanism

Multiple commercially sold metal seals are available. These require high forces applied to compress the metal seal and achieve a negligibly low leak rate.

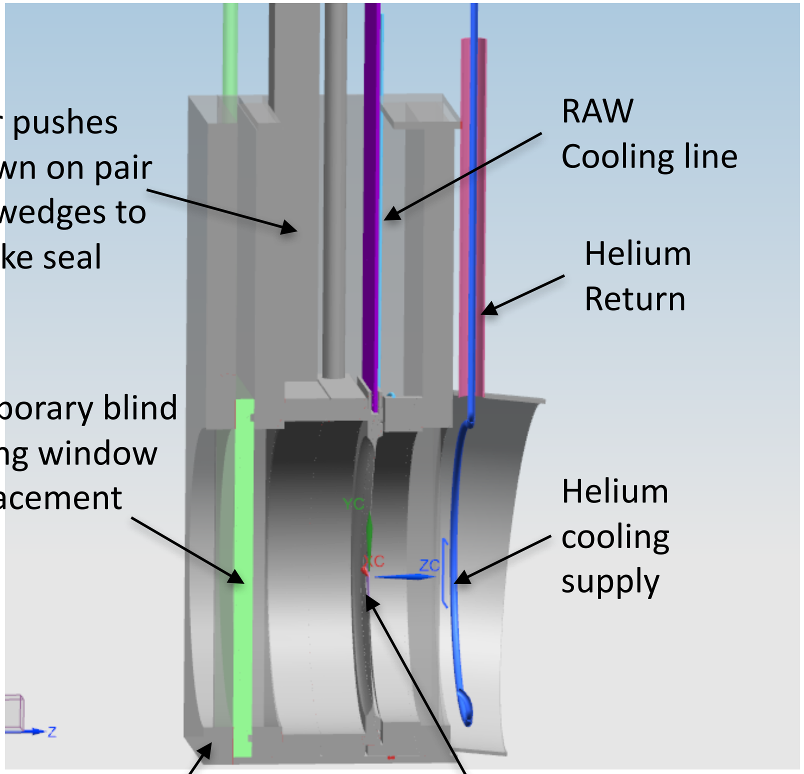
- Initial testing at Fermilab indicates that for low differential gas pressure across the seal, the compressive load on the seal can be reduced significantly.

Have two viable solutions to apply the seal load:

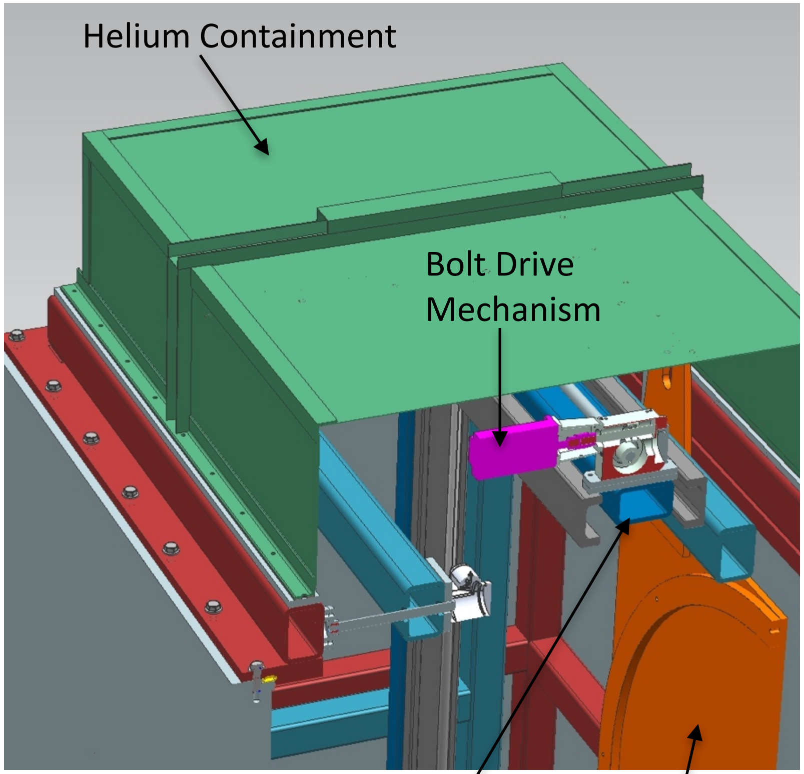
1. Use a pair of wedges to apply the seal compressive load via hydraulic actuators located on top of the shielding.
2. Use a traditional bolted seal arrangement and use a dedicated purpose machine to tighten or loosen bolting with a remotely located operator.
   - Similar to a machine already in development for the Mu2e target station.

Possible solutions to apply the US Window Seal Load

1. Wedge Seal Compression Design (X-Section)



2. Bolted Seal Design (Upper Portion)



These are concepts at this time, much work remains to be done to come up with the final solution.

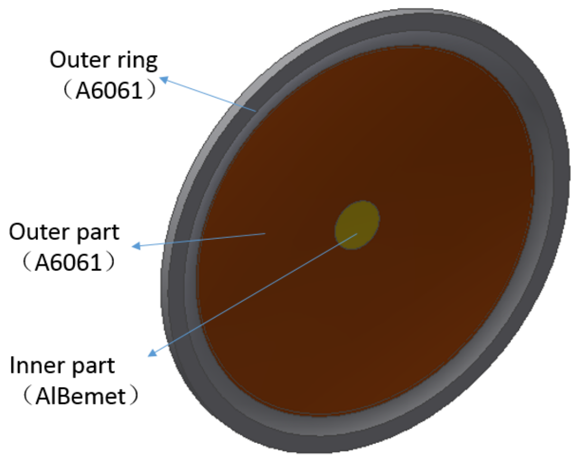
Decay Pipe US Window and the Decay Pipe Helium:

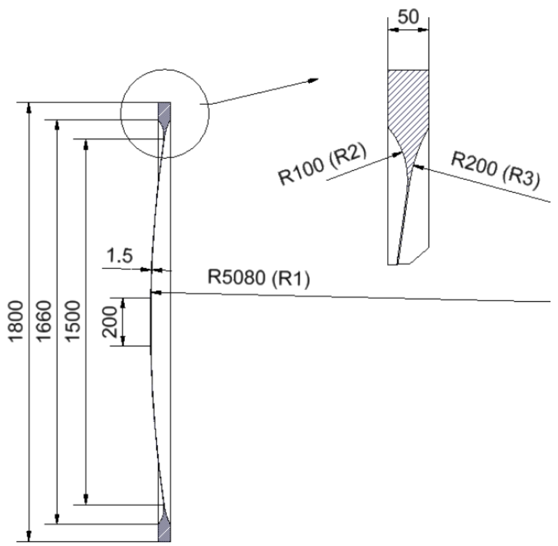
What to do with the Helium during window replacement:

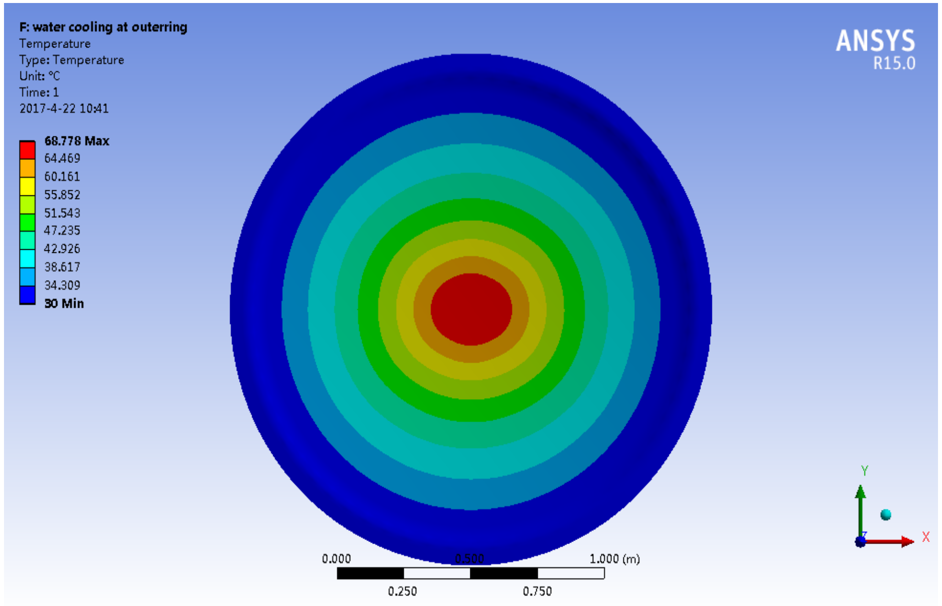
110,000 cubic feet (3,150 m^3) of Helium in decay pipe at 1.5 psig (1.11 bar). Potential solutions include:

- Vent the helium, replace window, repeat the purge and helium fill.
  - Easy solution, but results in helium loss.
- Recover helium from the decay pipe, store, and use recovered helium to repeat the purge and helium fill.
  - Slightly more difficult as a high pressure compressor is needed.
- Incorporate an ‘Air-Lock’ (Helium Containment) in the Window Replacement Tooling.
  - Requires more design effort, but inherently provides contamination control and reduces the time required for a window replacement operation.

Decay Pipe US Window Thermal FEA – Optimized Config. 2.4 MW





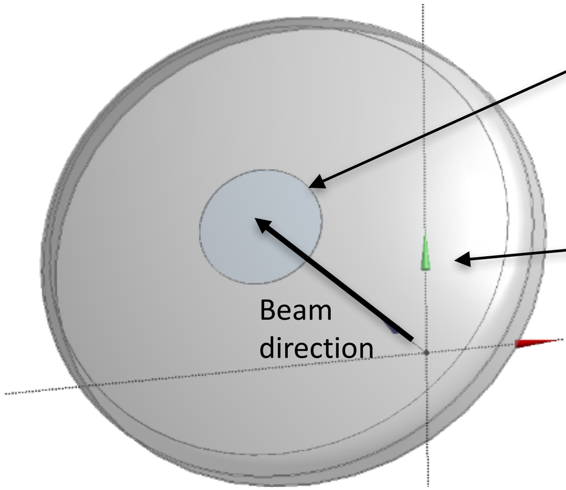


Maximum window temperature is 69°C with water cooling at the outer perimeter.

Likely will incorporate both a water cooled perimeter and a convectively cooled center section.

Decay US Window is replaceable.

Decay Pipe DS Window Thermal FEA – Optimized Config. 2.4 MW



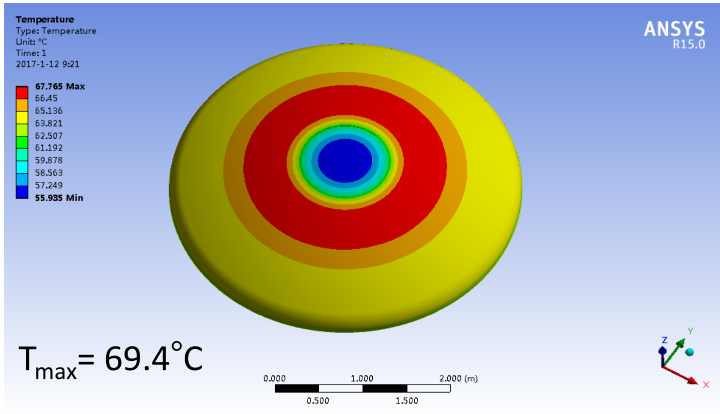
Inner segment is 1 m in diameter

a) Al-6061 -- t = 6.35 mm

b) or A414 Steel -- t = 3.42 mm

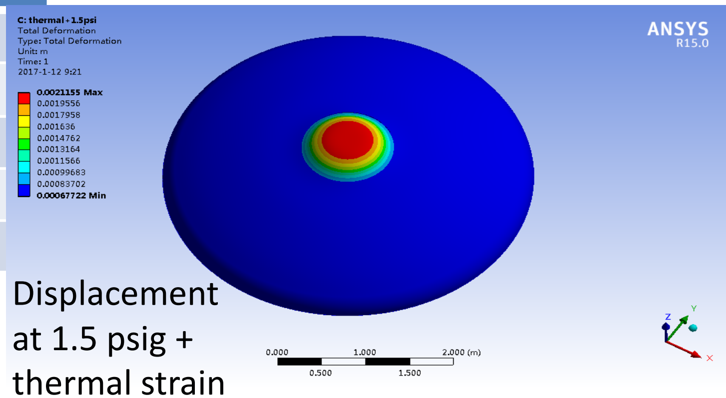
Outer segment is A414 steel, t = 12.7 mm

The window is tori-spherical with inner sphere radius of 4 m



Al-Steel Window

	Al-Steel window	Steel-Steel window
Highest temperature (°C)	69.4	70.5
Max. displacement at 1.5 psi (mm)	2.1	0.8
Max. Von Mises Stress at 1.5 psi (MPa)	37.7	33.3
Max. displacement at 5psi (mm)	2.8	1.1
Max. Von Mises Stress at 5 psi (MPa)	44.0	44.2

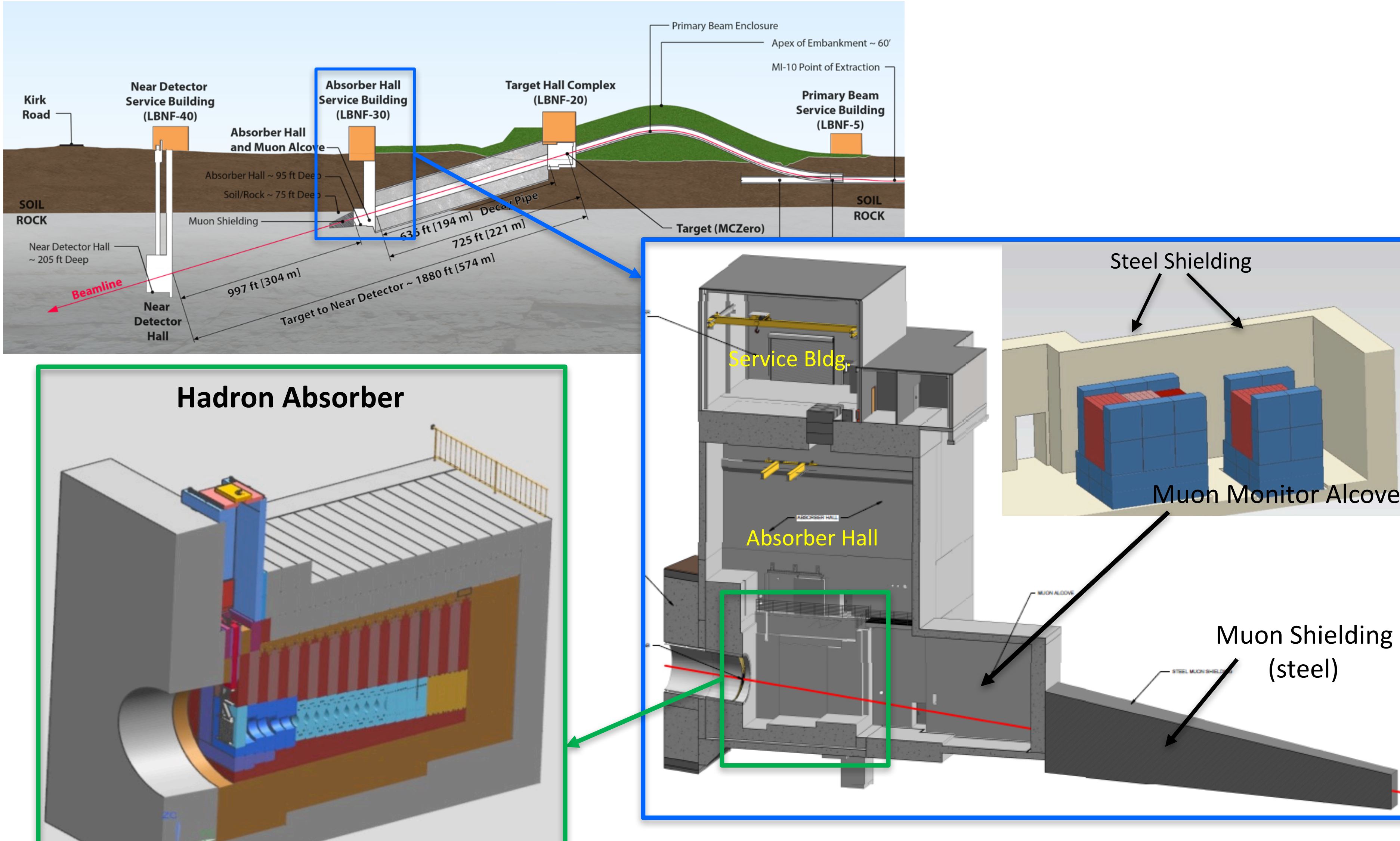


Material Strength	A6061-T6	A414
Yield tensile strength at 100 °C (Mpa)	262	230
Allowable stress for A6061-T6 from -28°C to 120 °C (MPa)	120	108

The stresses and temperature are acceptable.

Absorber Design (*Conceptual*)

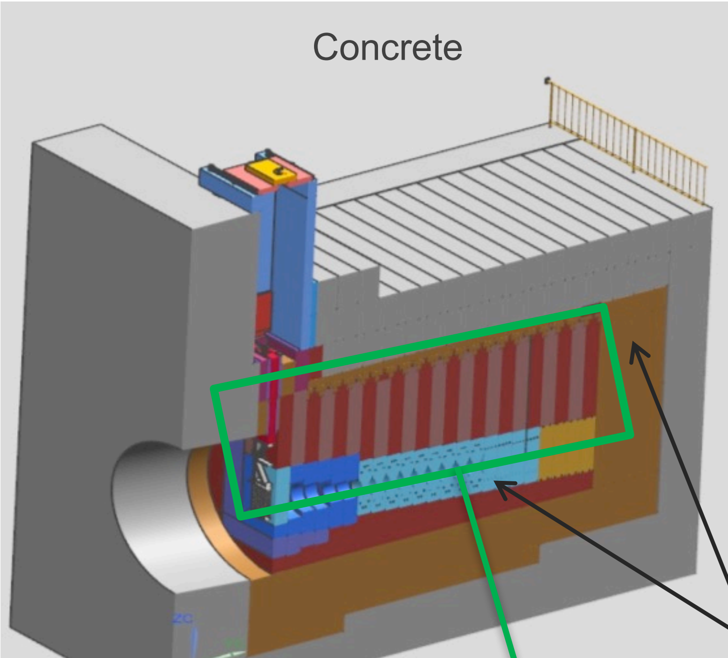
LBNF Hadron Absorber



Absorber Overview

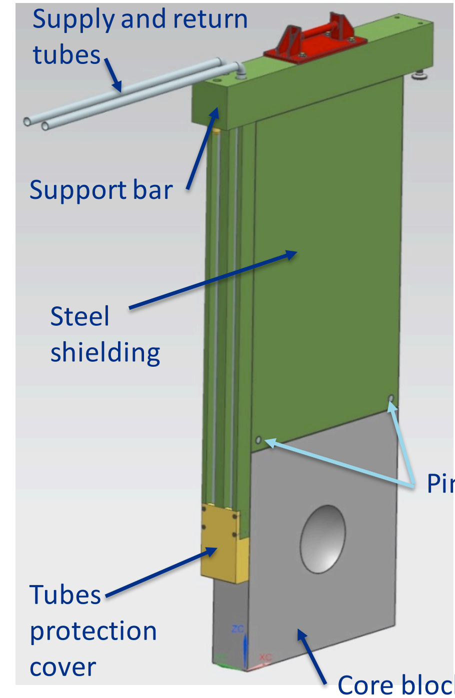
- Located directly downstream of the decay pipe – made up of actively cooled Aluminum and Steel blocks surrounded by concrete.
  - Majority of beam power is deposited in the absorber core which is water cooled and replaceable. Surrounding steel and concrete shielding is air-cooled.
- Provides radiation protection to people and keeps soil/groundwater activation levels to below allowable limits.
- Designed for the worst case condition at 2.4 MW operation:
  - Shortest possible decay distance [221m from MCZero to end of decay pipe]
  - Helium filled decay pipe
  - Shortest target envisioned at 2 interaction lengths (Reference design)
  - Designed to sustain 2 successive beam accident pulses – interlock system limits the accident pulses to 2.
- The optimized design reduces energy deposition by almost factor 2 – therefore room for value engineering and further optimization of the Absorber design.
- Successful & comprehensive technical design review held on Jan 2015 with intl. participation, reviewers gave the conceptual design a "clean pass".

Absorber Core (water cooled)

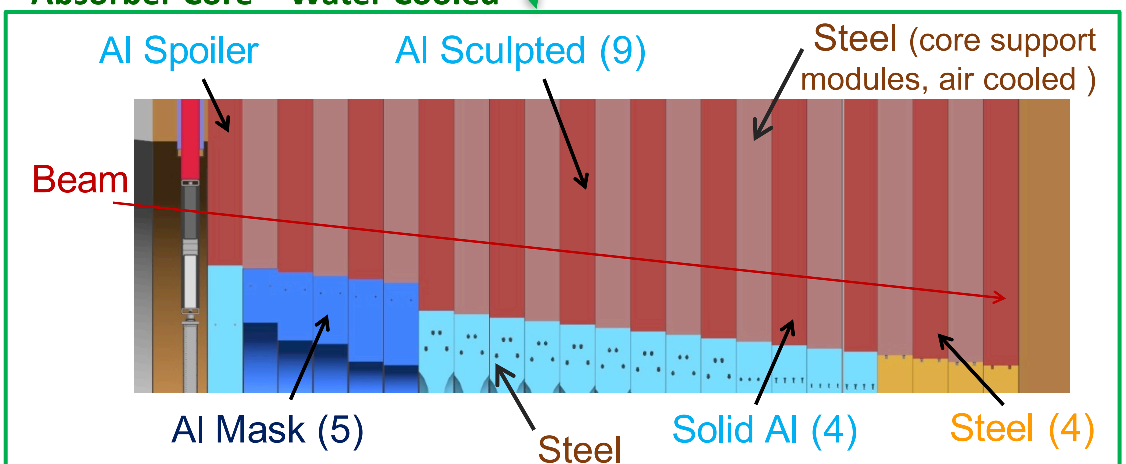


- Made of removable, water-cooled Al and Steel "T-Blocks" (based on NuMI T-Block design)
- Gun drilled water channels in core blocks.
- Flexible, modular design that can be repaired/replaced or upgraded in the future.

Absorber Core Module Assy.

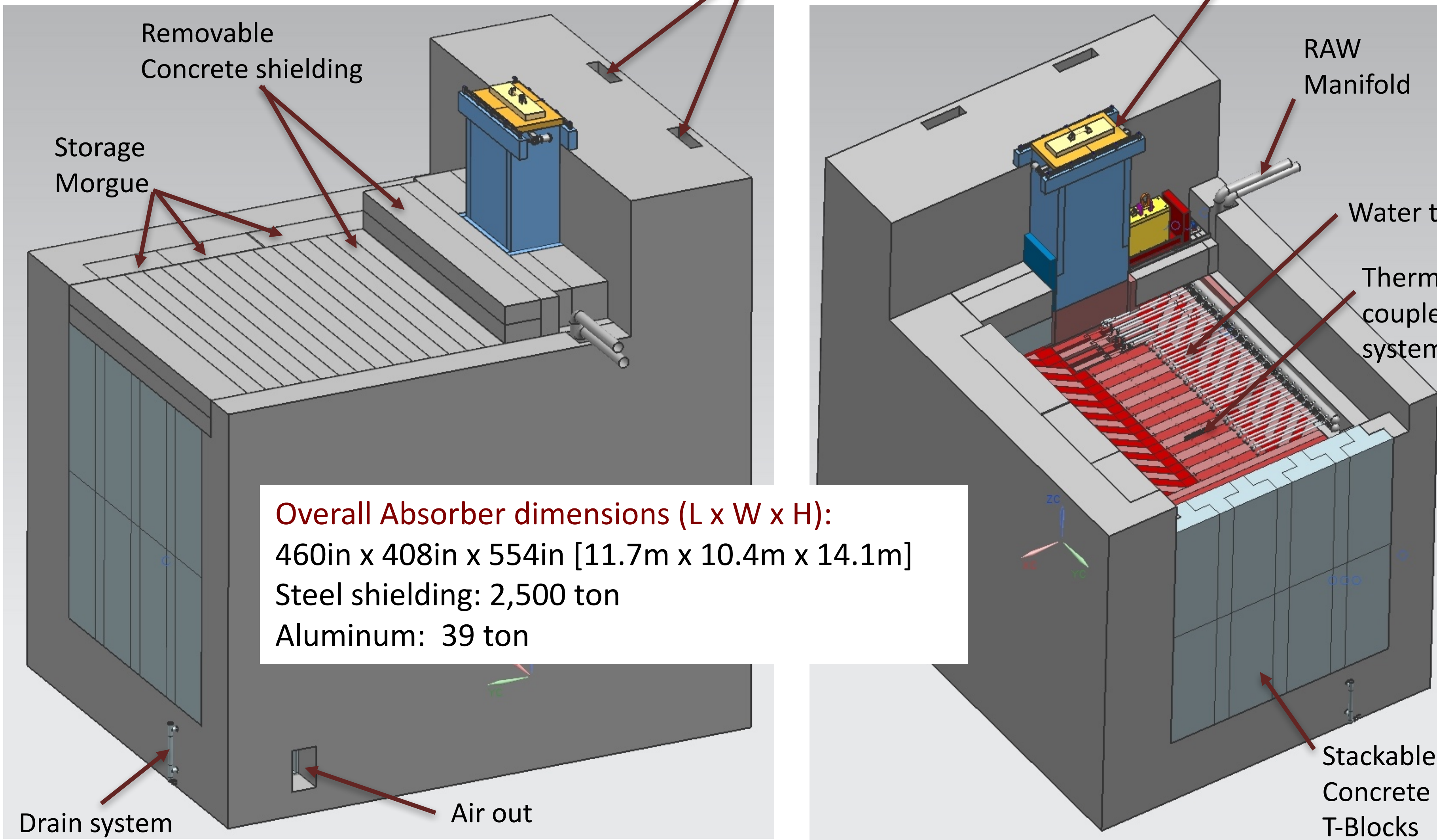


Absorber Core – Water Cooled



NuMI T-Block

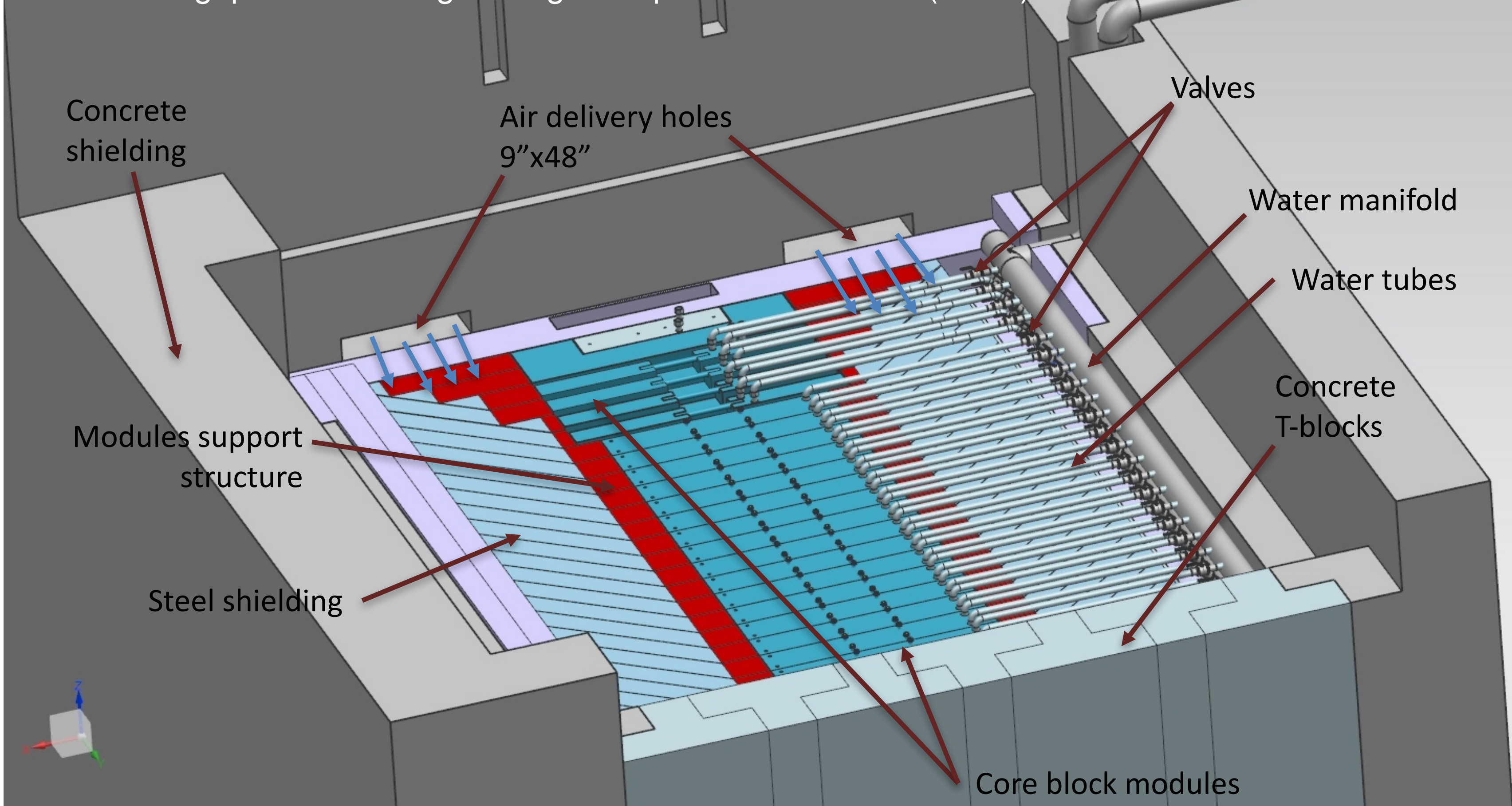
Absorber Design



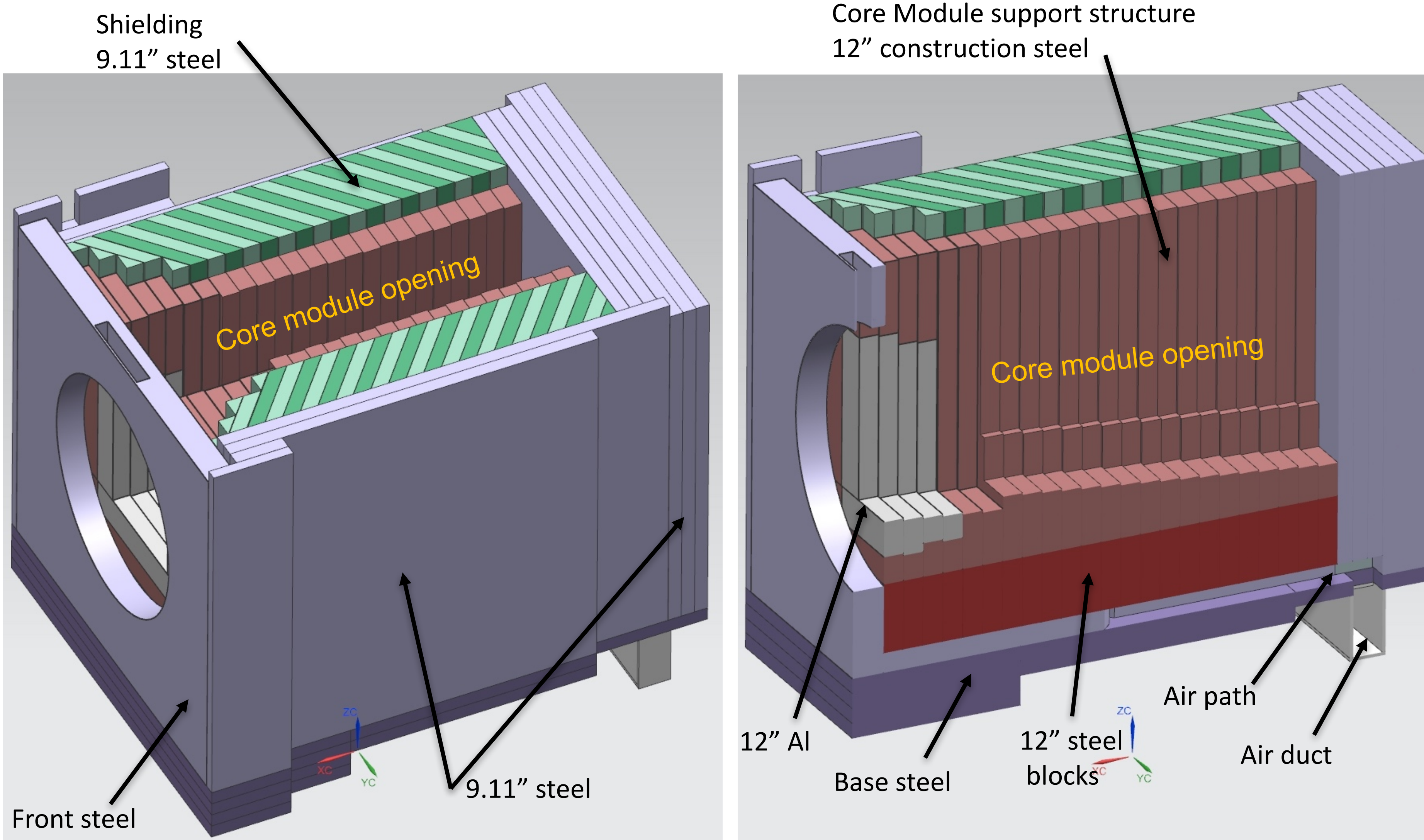
Overall Absorber dimensions (L x W x H):
460in x 408in x 554in [11.7m x 10.4m x 14.1m]
Steel shielding: 2,500 ton
Aluminum: 39 ton

Absorber Design

- Air cooling system removes ~225 kW from the steel shielding surrounding the absorber core for the reference design (much less for the optimized design).
- Steel shielding is made from CCSS 9.11 inch steel plates.
- Core module blocks are made from 12 inch construction steel.
- Air flow gap between neighboring steel plates is 0.20 inch (5 mm)

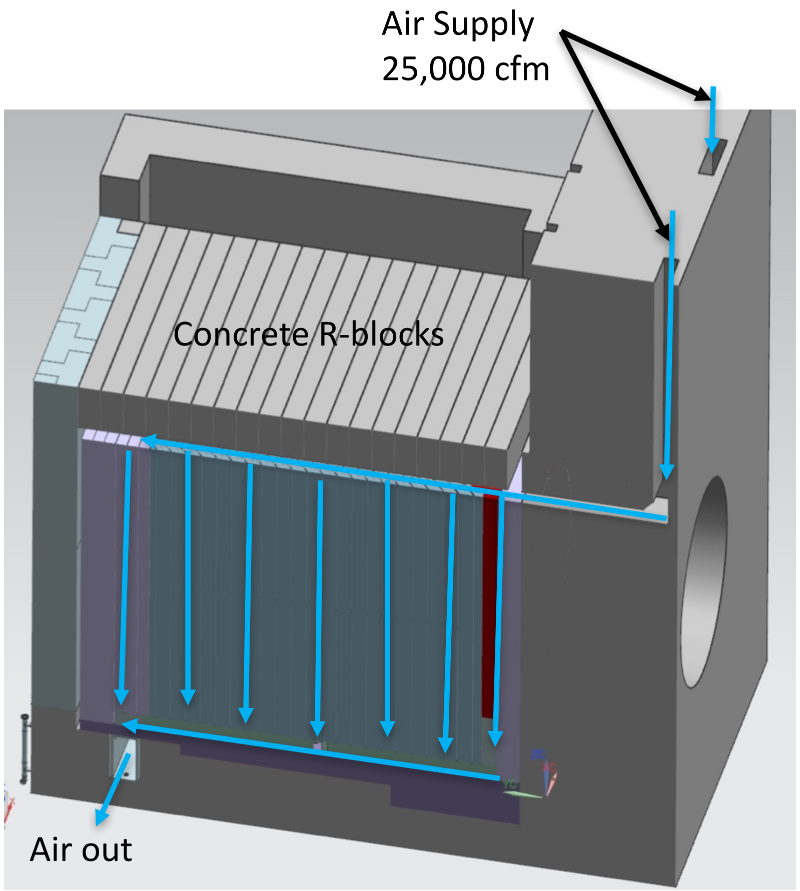


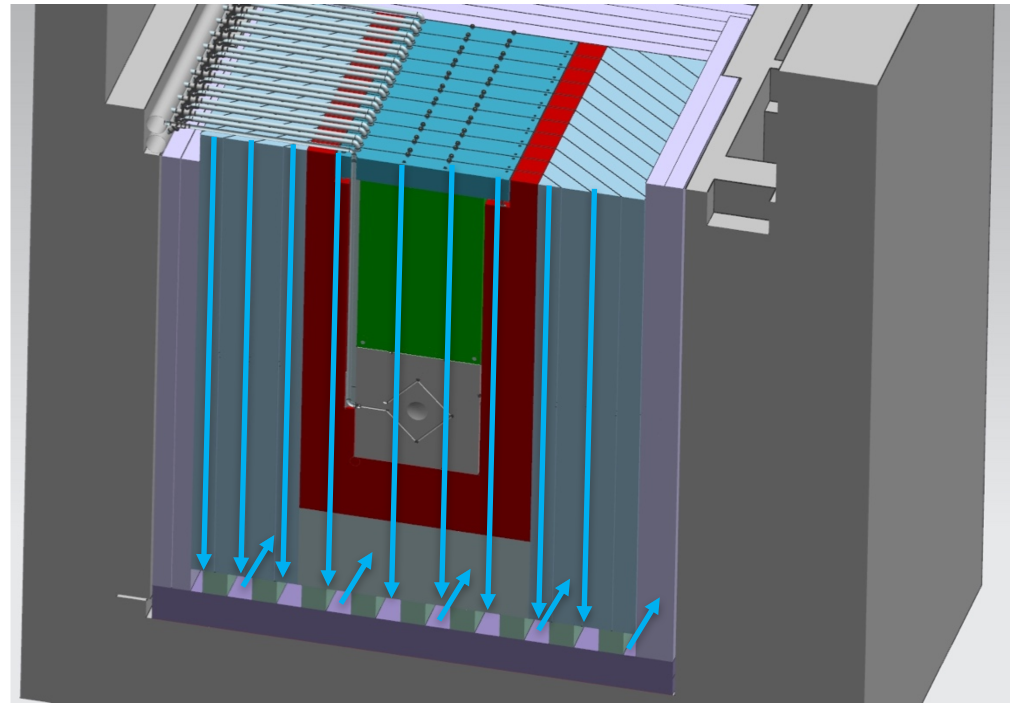
Absorber Design – Steel Shielding



Overall dimensions (L x W x H): 355in x 285in x 295in [9m x 7.25m x 7.5m]

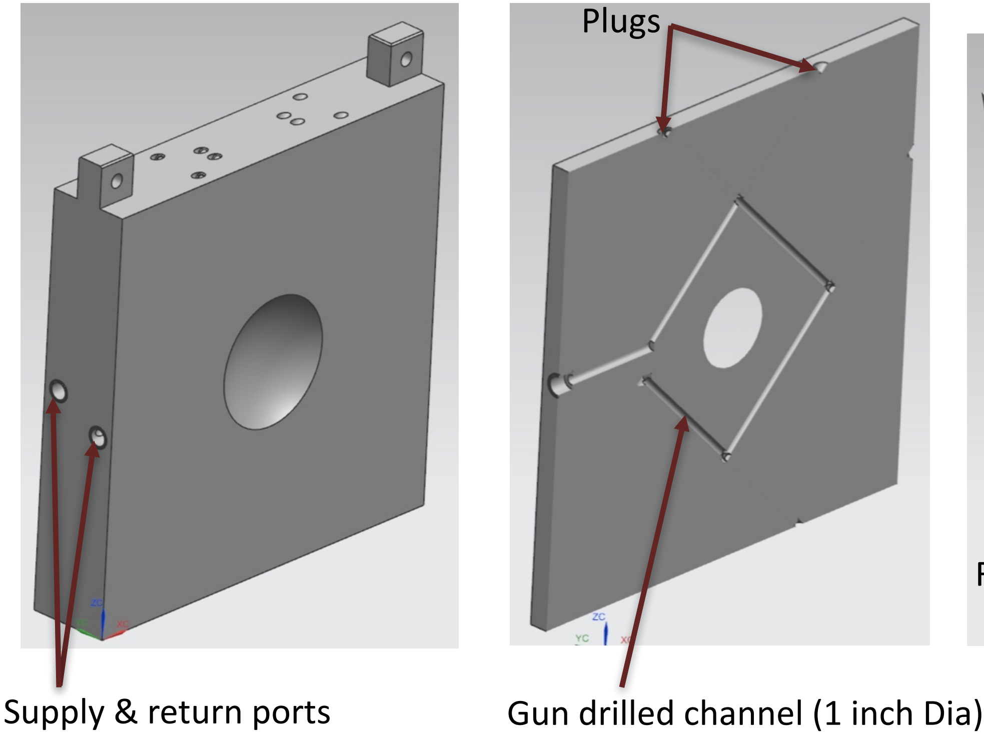
Absorber Design – Air Flow

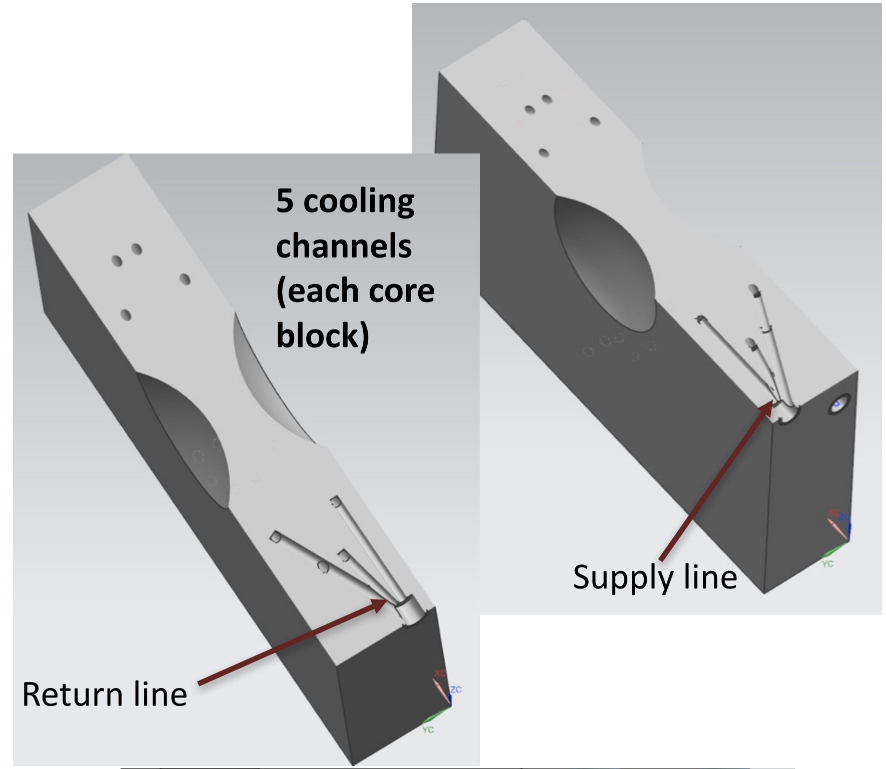




Air flow gap between adjacent steel plates is 0.20 inch (5 mm)

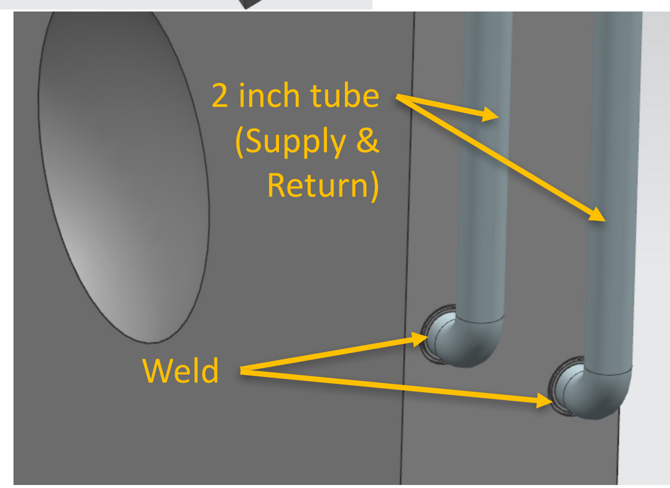
Absorber Design – Core Blocks



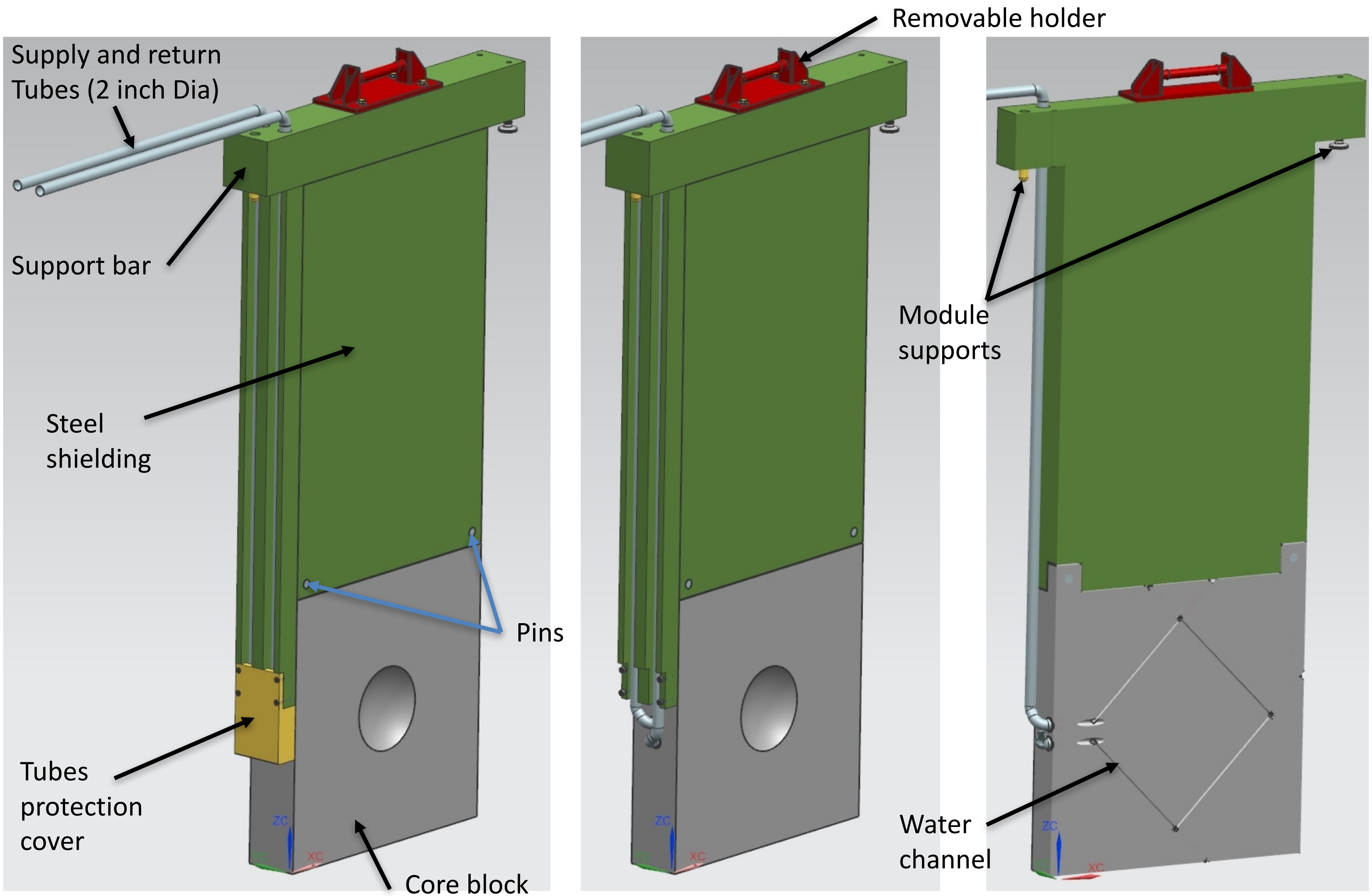


- Material: 6061-T6 Aluminum
- 5 gun-drilled cooling channels that consolidate to 1 supply and 1 return line.
- Core Block Dimensions:

60 in x 60 in x 12 in [1.5 m x 1.5 m x 0.31 m]

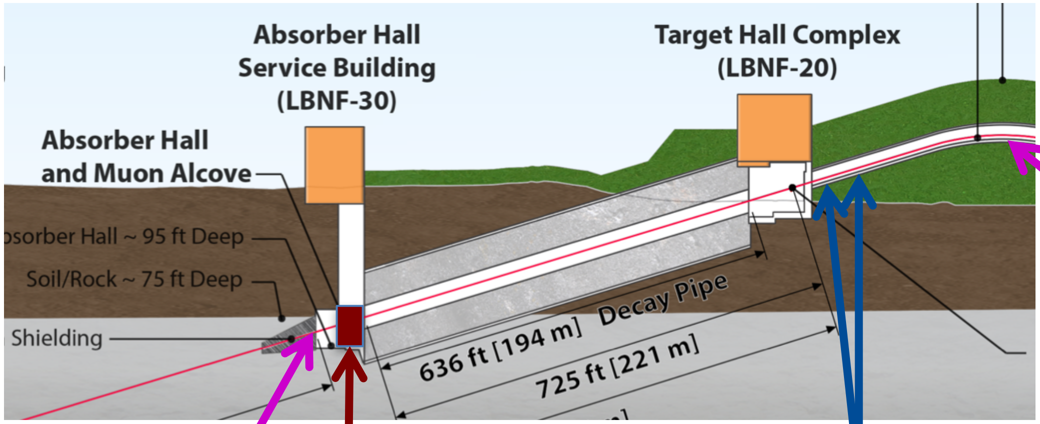


Absorber Design – Core Module Assembly



Absorber Design – Hardware Safety Systems

- Three independent systems provide redundancy to pull beam permit quickly in non-normal (beam accident) condition



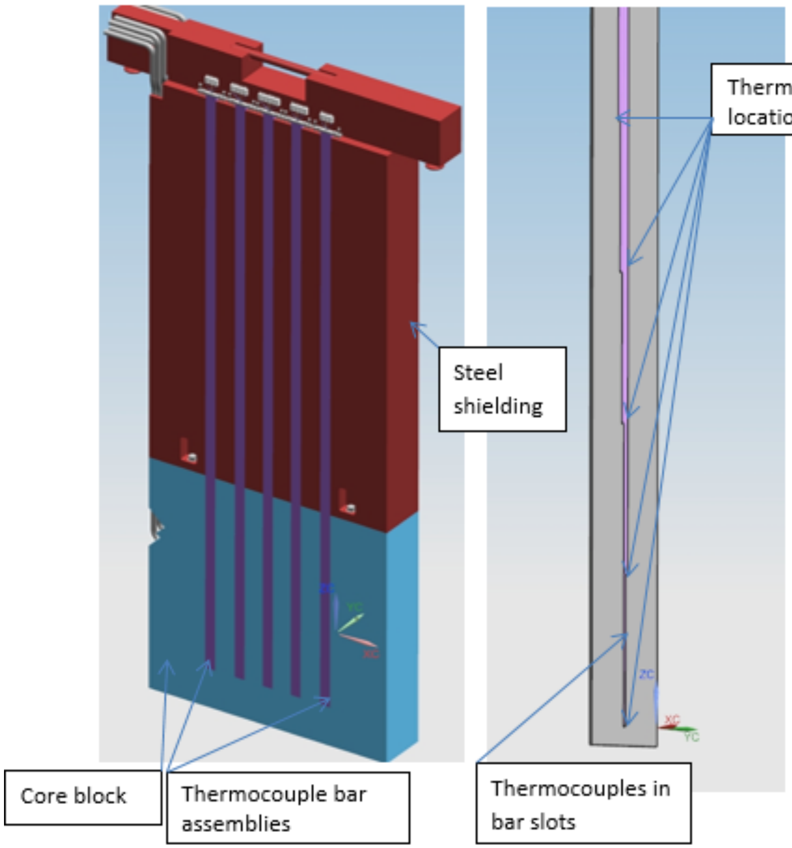
- **Beam position monitors** upstream of target
  - Pull beam permit after 1 beam spill if proton trajectory is off, missing target

- **Thermocouples** in absorber core
  - with thermocouple on-axis in shower, provides fast response (detects energy deposition in thermocouple itself)

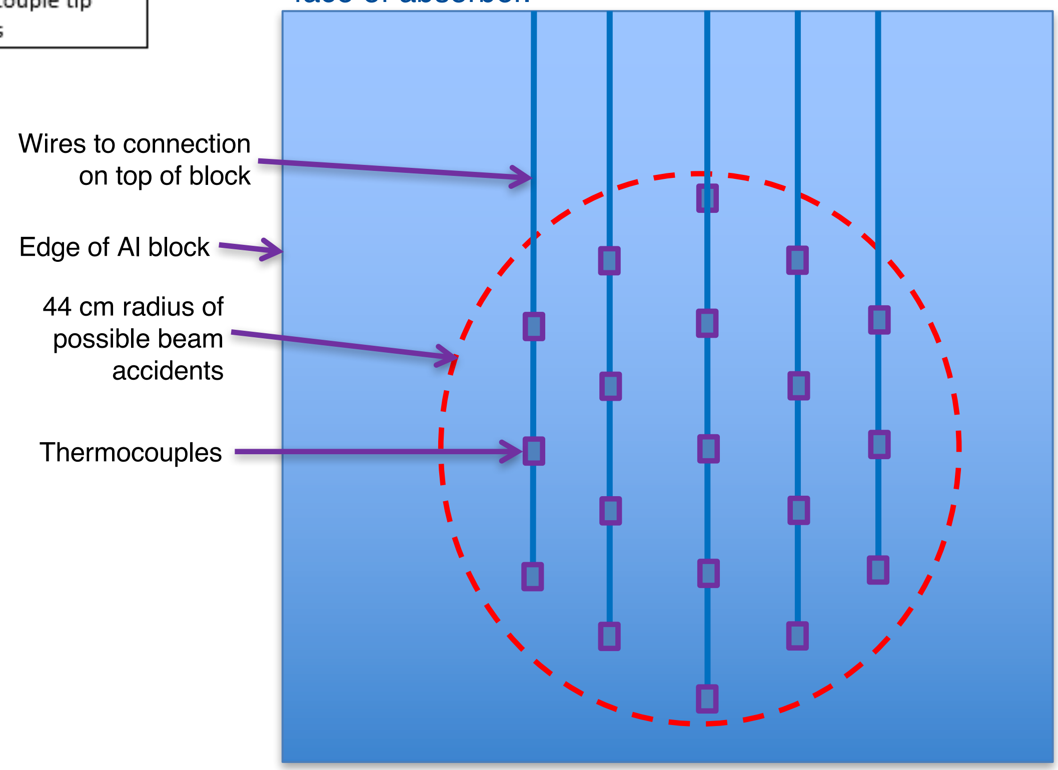
- **Muon monitor** after absorber combined with **Toroid proton monitor** before target
  - Can pull beam permit after 1 beam spill, if muon response is not proportional to number of protons in spill

Absorber Design – Thermocouple System in Absorber Core

- Thermocouple bars provide a replaceable array of thermocouples to monitor temperature in select core blocks. The bars are held into the core block by a T-shaped slot.



Example of an array that if installed on solid AL block 2 would pull the permit in a single pulse for a half-intensity accident pulse anywhere on reachable face of absorber.



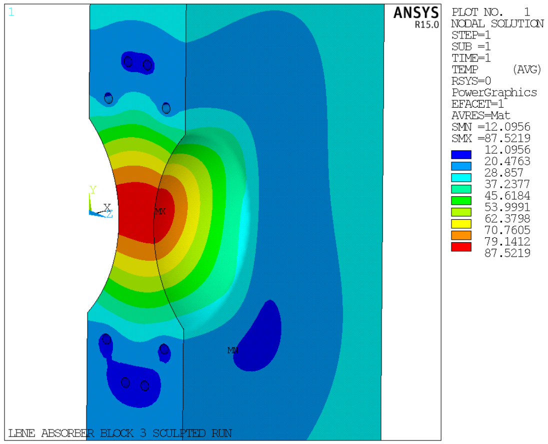
Absorber Design – FEA of Core Blocks at 2.4 MW (Ref. Design)

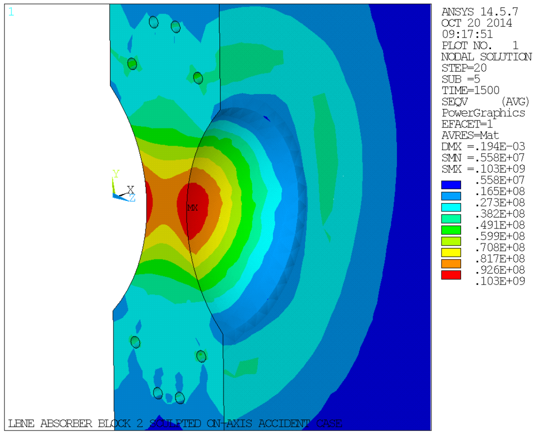
- Thermal and stress analysis completed for both steady state and accident conditions. All temperatures and stresses are within allowable limits.
- To minimize creep risk, Aluminum 6061-T6 temperatures kept under 100°C and stress under 170 MPa (from NuMI experience).
- DPA is well below limits with no effect on specific heat, swelling, elongation, and tensile properties.

Steady State Results

3rd Sculpted Al Block

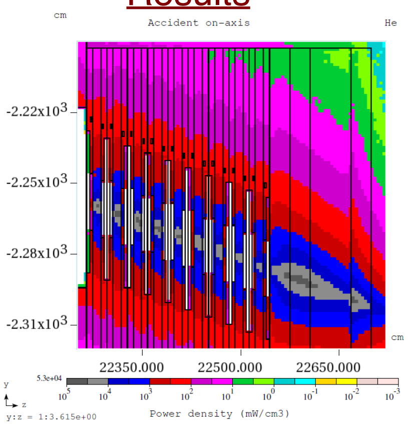
88°C max. temp.

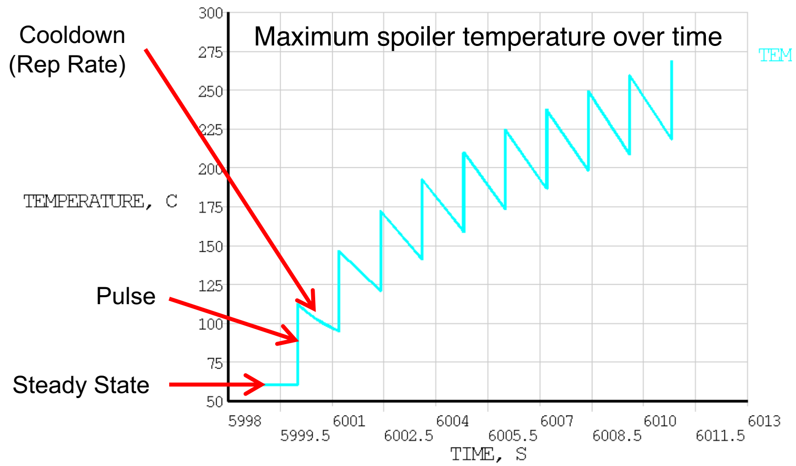




103 MPa max. compressive stress
Yield at 92°C: 232 MPa

On-Axis Accident Results



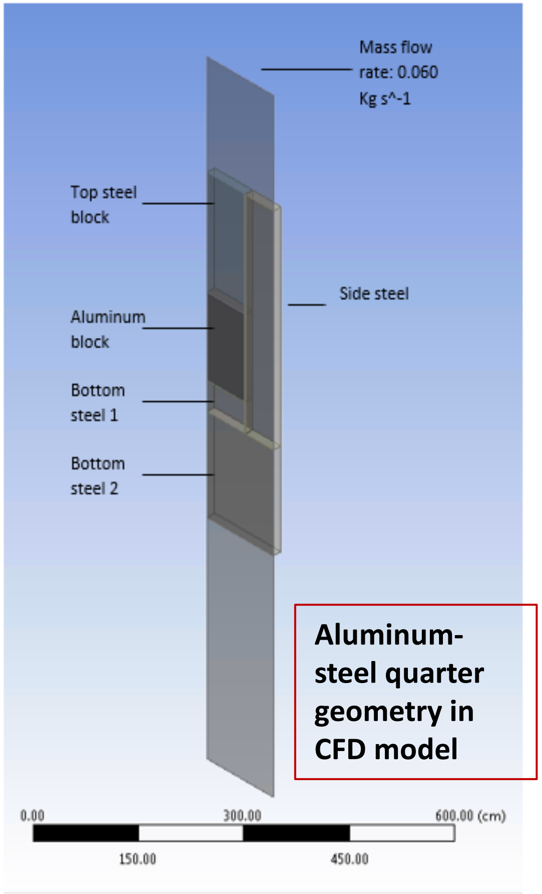


Yield for Al 6061-T6 at 150°C is 190 MPa

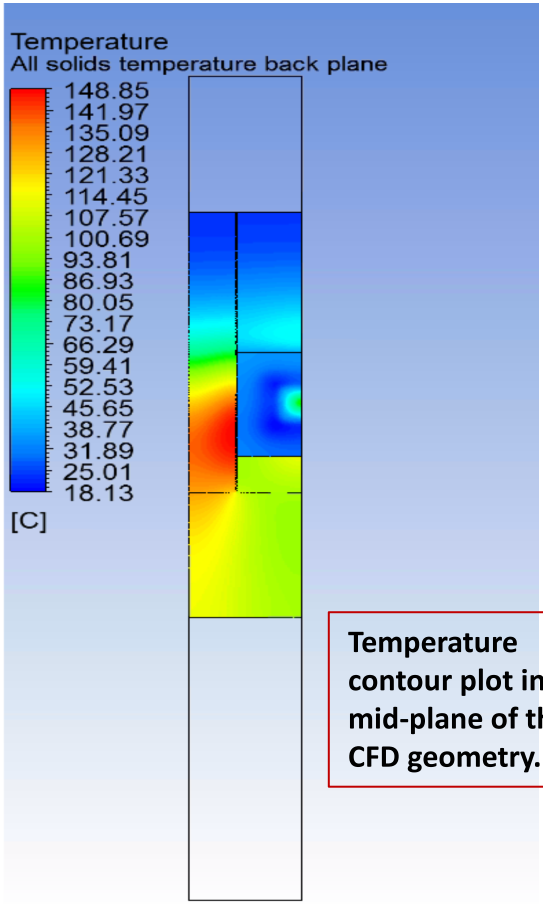
	Temperature after 2 accident pulses (°C)	Von-Mises Stress after 2 accident pulses (MPa)	Temperature rise per accident pulse (°C)
Spoiler	146	121	50
2nd Sculpted Al	140	148	38
2nd Full Al	120	63	18
1st Steel	242	199	10

Absorber Design – CFD Analysis of Air-Cooling at 2.4 MW (Ref. Design)

- CFD analysis completed using ANSYS CFX on section of Absorber that sees the maximum energy deposition.



Aluminum-steel quarter geometry in CFD model



Temperature contour plot in the mid-plane of the CFD geometry.

Results:

Average air velocity in the gaps was computed to be ~17m/s, with an estimated maximum temperature in the steel of **~149ºC** and peak air temperature of **~135ºC**.

The maximum allowable temperature for the steel is **260ºC** (based on allowable temperatures for the paints used to coat the steel for corrosion protection).

Summary & Conclusion

Summary & Conclusion

- The conceptual designs for the LBNF Target Station, Decay Pipe, and Absorber have been presented. The designs follow the NuMI facility closely plus also incorporate lessons learned from other facilities.
- There was a recent change from air to inert gas (N_2) in the target chase – this resulted from air-release studies that showed air is no longer viable with the longer and wider chase (adopted at CD1-R to allow for an optimized target-horn configuration).
- Prototypes for the hatch cover sealing system and stripline feedthrough will need to be developed and tested to validate the designs and determine leak-rates.
- Prototype to validate the convection coefficient for the Cooling Panels using the Platecoil heat exchanger will also need to be developed.
- Many challenging and interesting technical areas to work on – significant work still remains to be done going in to preliminary design.
- Looking for partners interested in working with us on some of these systems!

Thank you.
Questions?